DESIGN OF BOOST CONVERTER FOR EDUCATIONAL TEST BENCH

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ABSTRACT

DESIGN OF BOOST CONVERTER FOR EDUCATIONAL TEST BENCH

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In this thesis a boost converter is developed to be used as a test bench in power electronics laboratory. For this purpose, first, steady-state and small-signal analyses of a boost converter are carried out, then closed loop control of the converter is developed and simulated. Then, the circuit is designed and manufactured. The test results are compared with the simulation results. Finally, an experimantal procedure is prepared to enable the students to perform the experiment in the laboratory with the test bench developed.

Keywords: Boost Converter, Small-Signal Analysis, MATLAB, PI.

ÖZ

EĞİTİM AMAÇLI YÜKSELTİCİ DÖNÜŞTÜRÜCÜ TASARIMI

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Bu tezde güç elektroniği ders laboratuvarlarında kullanılmak üzere yükseltici dönüştürücü devresi geliştirilmiştir. Bu amaçla ilk olarak yükseltici dönüştürücü devrelerinin sabit durum ve küçük işaret analizleri yapılmış, daha sonrasında devrelerin kapalı çevrim kontrolü gerçekleştirilmiş ve simüle edilmiştir. Daha sonrasında devre dizayn edilmş ve üretilmiştir. Test sonuçları simülasyon sonuçları ile karşılaştırılmıştır. Son olarak geliştirilen deney seti ile öğrencilerin laboraturda deneyi gerçekleştirebilmeleri için bir deney prosedürü hazırlanmıştır.

Anahtar Kelimeler: Yükseltici Dönüştürücü, Küçük Sinyal Analizi, MATLAB, PI.

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CHAPTER 1

DC-DC CONVERTERS

1.1 Overview

DC-DC converters are important in portable electronic devices such as cellular phones and laptop computers, which are supplied with power from batteries. Such electronic devices often contain several subcircuits where each requires a unique voltage level different from that supplied by the battery (sometimes higher or lower than the battery voltage, or even negative voltage). DC-DC converters offer a method of generating multiple controlled voltages from a single variable battery voltage, thereby saving space instead of using multiple batteries to supply different parts of the device. [1]

In most electronic systems, DC-DC voltage regulation (DC-DC convertion) is required for various functions. Today's complex electronic systems are requiring greater regulating performance, higher efficiency and lower parts count. Present integrated circuit and power package technology has produced IC voltage regulators which can ease the task of regulated power supply design, provide the performance required and remain cost effective.

DC-DC voltage regulators (converters) are often used to provide a regulated voltage supply from an unregulated voltage source. Unregulated voltage sources can be rectified line voltages that exhibit fluctuations due to changes in magnitude. Regulated voltage supplies provide an average DC output voltage at a desired level (3.3 V, 2.5 V, etc.), despite fluctuating input voltage sources and variable output loads. Factors to consider when deciding on a regulated voltage supply solution include [2]:

- Available source input voltages
- Desired supply output voltage magnitudes
- Ability to step-down or step-up output voltages, or both
- DC-DC converter efficiency (POUT / PIN)
- Output voltage ripple
- Output load transient response
- Solution complexity (one IC solution, # of passive components, controller and external FETs)

DC-DC voltage regulators (converters) often use one of the two methods to regulate the input voltage. The different types of the voltage regulation are:

- Linear Regulation
- Switching Regulation

In linear regulation, the main principle is comparison of input voltage to a reference voltage and dissipation (by heat) of any difference between the two [3].

In switching regulation, the main principle is switching input voltage "on" and "off" (pulses) in order to obtain a desired voltage. External capacitance and inductance are used to convert these pulses to a DC voltage. This method is basically different from linear regulation by its smaller power consumption. The regulation detail will be given later [3].

The voltage regulation is performed by different types of regulators. The next section aims at understanding the basics of the voltage regulators used in different applications.

1.2 Switching Regulators

Instead of controlling a variable resistance, the output of a switching regulator is controlled by rapidly switching a series device on and off. The duty cycle of the switch sets how much charge is transferred to the load. This is controlled by a similar feedback mechanism as in a linear regulator. Because the series element is either fully conducting, or switched off, it dissipates almost no power; this is what gives the switching design its efficiency. Switching regulators are also able to generate output voltages which are higher than the input, or of opposite polarity - something not possible with a linear design [4].

Like linear regulators, nearly-complete switching regulators are also available as integrated circuits. Unlike linear regulators, these usually require one external component: an inductor that acts as the energy storage element. (Unfortunately, the inductor must be external because large-valued inductors tend to be physically large relative to almost all other kinds of componentry; because of this, they are impossible to fabricate within integrated circuits) [4].

Switching voltage regulators are commonly used for both step-up and step-down applications, and differ from linear regulators by means of pulse-width modulation (PWM) implementation. Switching regulators control the output voltage by using a switch (may be internal or external to the IC regulator) with a constant frequency and variable duty-cycle. Switching frequencies are generally from a few kHz to a few hundred kHz. The switch duty-cycle ratio determines how much and how quickly the output supply voltage increases or decreases, depending on the load state and input source voltage. Some switching regulators utilize both variable switching frequency and duty-cycle [2].

The clear advantage of switching regulators is efficiency, as minimal power is dissipated in the power path (FET switches) when the output supply voltage is sufficient for the load state. Essentially, the power converter "shuts off" when power is not needed, due to minimal switch duty-cycle. The disadvantage of switching regulators is complexity, as several external passive components are required on board. Output voltage ripple is another disadvantage, which is generally handled with bypass capacitance near the supply and at the load [2].

1.2.1 Switching Regulator Types

The various topologies of DC-DC converters can generate voltages higher, lower, higher and lower or negative of the input voltage; their names are [1]:

- Buck
- Boost
- Buck-boost
- Inverting
- Forward
- Flyback converter
- Push-pull
- Half bridge
- Full bridge
- Ćuk
- SEPIC

The basic components of the switching circuit can be rearranged to form a step-down (buck), step-up (boost), or an inverter (flyback). These designs are shown in Figure 1, Figure 2, Figure 3 and Figure 4, respectively, where Figure 3 and Figure 4 are same except for the transformer and the diode polarity [5].

Isolated DC-DC converters convert a DC input power source to a DC output power while maintaining isolation between the input and the output, generally allowing differences in the input-output ground potentials in the range of hundreds or thousands of volts. They can be an exception to the definition of DC-DC converters in that their output voltage is often (but not always) the same as the input voltage [5].

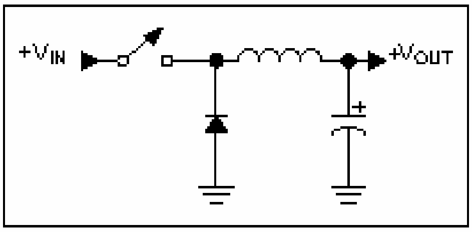

Figure 1 Buck converter topology.

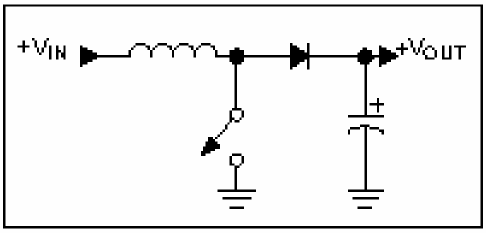

Figure 2 Boost converter topology.

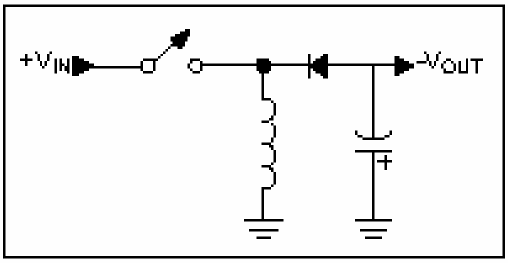

Figure 3 Inverting topology.

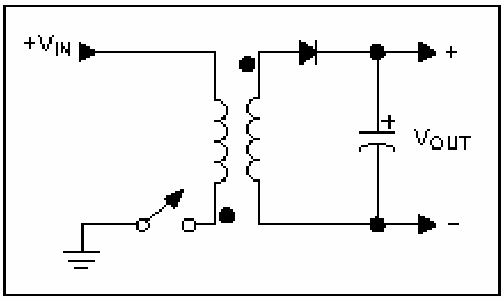

Figure 4 Transformer flyback topology.

1.3. Boost Converter

1.3.1 Seady State Continuous Conduction Mode

Boost converter is a DC-DC converter that steps up the dc voltage from its fixed low level to a desired high level. Its circuit topology is given in Figure 5.

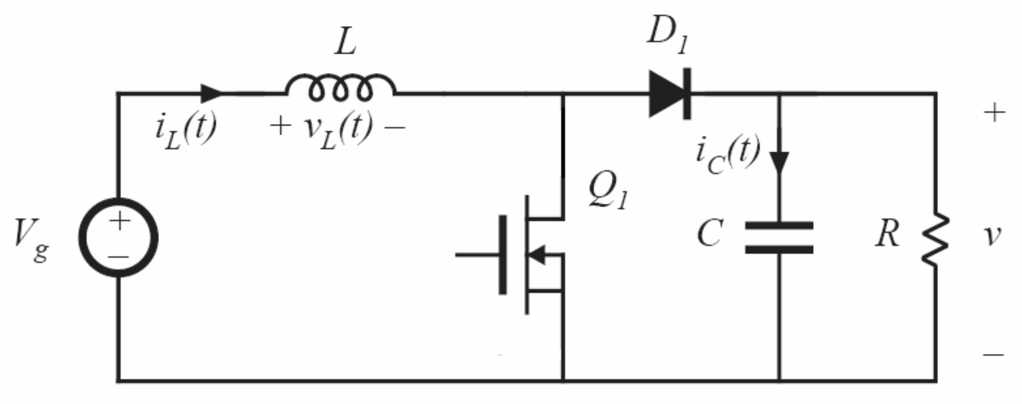

Figure 5 Boost converter.

During the on time the inductor current increases from its minimum value toward its maximum value [7]. In other words, the stored energy in the inductor increases during the time the switch is in the closed position [7]. During the off time, T_{OFF} = (1 - D)T,. the switch is open and the inductor current is directed toward the load via diode D. The inductor current therefore charges the capacitor and supplies the load current. The diode D blocks not only the current flow toward the source when the switch is in the closed position but also stops the output voltage from appearing across the closed switch [7]. The inductor also helps control the percent current ripple and determines whether or not the circuit is operating in the continuous conduction mode. The capacitor C provides the filtering action by providing a path for the harmonic currents away from the load. In addition, its value is large enough so that the output voltage ripple is very small.

The analysis begins when the inductor current is at its minimum and the switch S is closed at t = 0. The differential equation for the inductor current, for $0 \le t \le T_{ON} = DT$, and its solution are [7]:

$$L\frac{di_L(t)}{dt} = V_S$$

$$i_L(t) = \frac{V_S}{L}t + I_{L,\min}$$

According to this equation, the inductor current increases linearly and attains its maximum value $I_{L.max}$ as $t = T_{ON} = DT$ such that [7]:

$$I_{L,\max} = \frac{V_S}{L}DT + I_{L,\min}$$

Defining the change in the current from its minimum to maximum value as the peak-to-peak current ripple ΔI_L, the above equation yields an expression for ΔI_L as [7]:

$$\Delta I_L = I_{L,\max} - I_{L,\min} = \frac{V_S}{L}DT$$

As soon as the inductor current reaches its maximum value, the switch is opened. The inductor current now begins to supply the load current and charge the capacitor. The corresponding differential equation for $T_{ON} \le t \le T$ is [7]:

$$L\frac{di_L(t)}{dt} = V_S - V_O$$

The solution of this equation yields

$$i_L(t') = \frac{V_S - V_O}{L}(t - DT) + I_{L,\max}$$

As per this equation, the inductor current decreases linearly from its maximum value at t = T_{ON} to its minimum value as t = T, such that [7]:

$$I_{L,\min} = \frac{V_S - V_O}{L}(1-D)T + I_{L,\max}$$

The peak-to-peak current ripple is:

$$\Delta I_L = I_{L,\max} - I_{L,\min} = -\frac{V_S - V_O}{L}(1-D)T$$

Two formulas found for the current ripple ΔI_L must be the same. Equating the two equations, the following is obtained [7]:

$$\frac{V_S}{L}DT = -\frac{V_S - V_O}{L}(1-D)T$$

This equation upon simplification yields:

$$V_O = \frac{V_S}{1-D}$$

The voltage convertion ratio M(D) is the ratio of the output to the input voltage of a dc-dc converter. The above equation predicts that the voltage convertion ratio is [7]:

$$M(D) = \frac{V_O}{V_S} = \frac{1}{D'} = \frac{1}{1-D}$$

The equation is plotted in Figure 6.

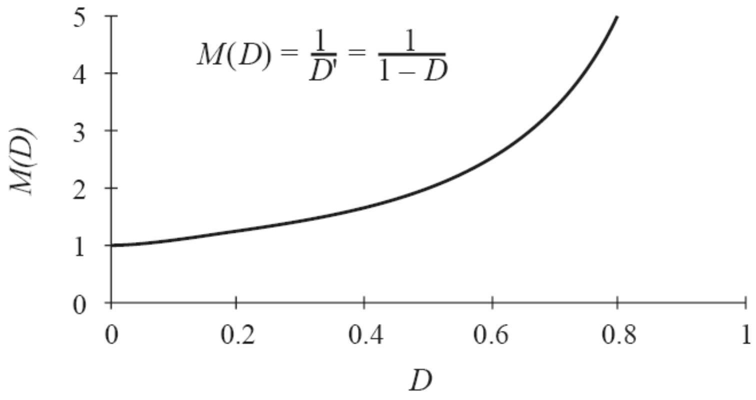

Figure 6 DC conversion ratio of boost converter.

Equation states that the output voltage of the boost converter is indirectly proportional to (1 - D) and directly proportional to the source voltage [7]. Since the duty cycle is usually less than unity, the output voltage is greater than the applied voltage [7]. This is the reason why a boost converter is commonly called the step-up converter. When the switch, the inductor, and the capacitor are treated as ideal elements, the average power dissipated by these components is zero [7]. Consequently, the average power supplied by the source must be equal to the average power delivered to the load. That is, [7]:

$$V_S I_S = V_O I_O = \frac{V_S}{1-D} I_O$$

This equation expresses the average source current in terms of the average load current as:

$$I_S = \frac{I_O}{1-D}$$

Since the source current is exactly the same as the inductor current, the average inductor current is [7]:

$$I_{L,avg} = I_S = \frac{I_O}{1-D}$$

The expressions for the maximum and minimum currents through the inductor are written as [7]:

$$I_{L,\max} = I_{L,avg} + \frac{\Delta I_L}{2} = \frac{V_O}{R(1-D)} + \frac{V_O}{2Lf}(1-D)D$$

$$I_{L,\min} = I_{L,avg} - \frac{\Delta I_L}{2} = \frac{V_O}{R(1-D)} - \frac{V_O}{2Lf}(1-D)D$$

The inductor current is sketched as shown in Figure 7. It also represents the source current [7].

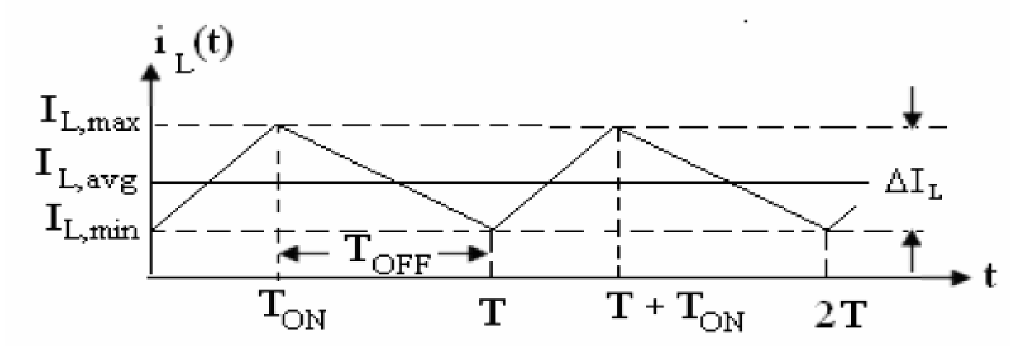

Figure 7 Inductor and the source currents.

The peak-to-peak current ripple is expressed in terms of the output voltage as:

$$\Delta I_L = \frac{V_S}{L} DT = \frac{V_O}{Lf}(1-D)D$$

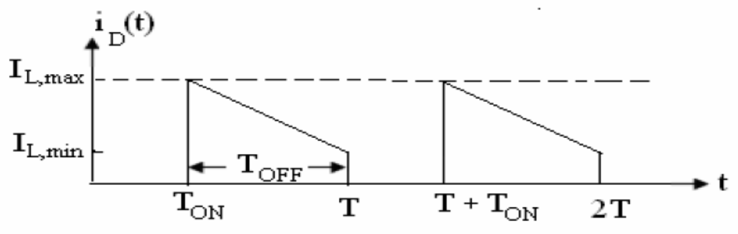

Figure 8 The diode current.

The current through the diode is shown in Figure 3. Its average value is [7]:

$$I_{D,avg} = \frac{I_{L,\max} + I_{L,\min}}{2} \frac{T_{OFF}}{T} = \frac{V_O}{R}$$

Since the average current in the diode is equal to the average current through the load resistor R, the average current in the capacitor, as expected, is zero [7]. When the switch is in its closed position, the capacitor supplies the load current. Hence, from $0 \leq t \leq T_{ON} = DT$, the capacitor current is [7]:

$$i_C(t) = -I_O = -\frac{V_O}{R}$$

When the switch is opened, the inductor current supplies both the capacitor current and the load current. Thus, during the time interval $T_{ON} \leq t' \leq T$, the capacitor current is [7]:

$$i_C(t) = i_L(t) - I_O$$

The maximum and minimum values of the capacitor current when the switch is in its open position can be written as [7]:

$$I_{C,\max} = I_{L,\max} - I_O = \frac{V_O D}{R(1-D)} + \frac{V_O}{2Lf}(1-D)D$$

$$I_{C,\min} = I_{L,\min} - I_O = \frac{V_O D}{R(1-D)} - \frac{V_O}{2Lf}(1-D)D$$

From these two equations, the following is obtained:

$$\Delta I_L = I_{C,\max} - I_{C,\min}$$

The capacitor current waveform is shown in Figure 12.

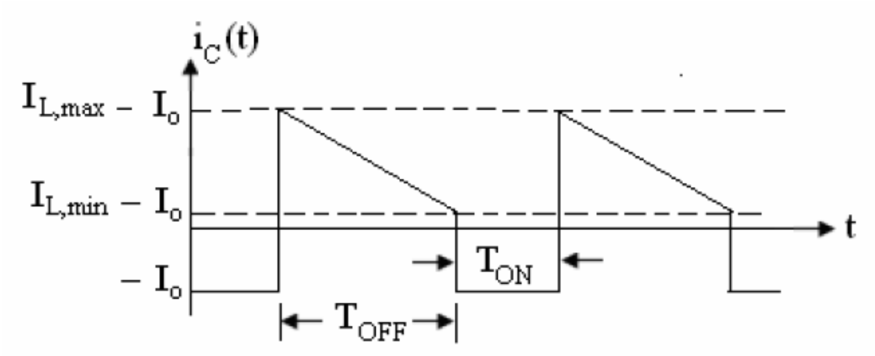

Figure 9 Current through the capacitor.

The current waveform of Figure 9 helps to determine the change in the voltage across the capacitor [7]. During the time the switch is closed, the charge on the capacitor is decreasing because the capacitor is supplying the current to the load [7]. The change in the charge is:

$$\Delta Q = -I_O T_{ON} = -\frac{V_O}{R} DT$$

The decrease in the charge will result in a decrease of the capacitor voltage from its average value of V_O [7]. Therefore, the magnitude of the change in the capacitor voltage is:

$$|\Delta V_O| = \frac{\Delta Q}{C} = \frac{V_O}{RC} DT$$

During the time the switch is open, the component of the inductor current that flows through the capacitor will increase the capacitor voltage by the same amount [7]. Hence, if the capacitor voltage ripple is defined as the ratio of the increase in the [7] capacitor voltage from its average value, it can be expressed as:

$$\frac{\Delta V_O}{V_O} = \frac{DT}{RC} = \frac{D}{RCf}$$

The peak-to-peak voltage ripple for the boost converter will be twice of that given in the above equation. This equation is viewed as one-sided voltage ripple.

1.3.2 Seady State Discontinuous Conduction Mode

When the diode conducts, its current is identical to the inductor current $i_L(t)$ [7]. As can be seen from Figure 8, the minimum value of the inductor current during the diode conduction subinterval $DT_S < t < T_S$ is $(I - \Delta i_L)$. If this minimum current is positive, then the diode is positive biased for the entire subinerval $DT_S < t < T_S$, and the converter operates in the continuous conduction mode [7]. So the conductions for operation of the boost converter in the continuous and discontinuous conduction modes are:

$$I > \Delta i_L \quad for \quad CCM$$

$$I < \Delta i_L \quad for \quad DCM$$

Substitution of the CCM solutions for I and Δi_L yields:

$$\frac{V_g}{D'^2 R} > \frac{DT_S V_g}{2L} \qquad \text{for CCM}$$

This equation can be rearranged to obtain:

$$\frac{2L}{RT_S} > DD'^2 \quad \text{for CCM}$$

Which is in standart form

$$K > K_{crit}(D) \quad \text{for CCM}$$

$$K < K_{crit}(D) \quad \text{for DCM}$$

where $K = \dfrac{2L}{RT_S}$ and $K_{crit}(D) = DD'^2$

The dependance of $K_{crit}(D)$ on the duty cycle D is plotted in Figure 13. $K_{crit}(D)$ is zero at D = 0 and at D = 1, and has a maximum value of 4/27 at D = 1/3. Hence, if K is greater than 4/27, then the converter operates in the continuous conduction mode for all D [7].

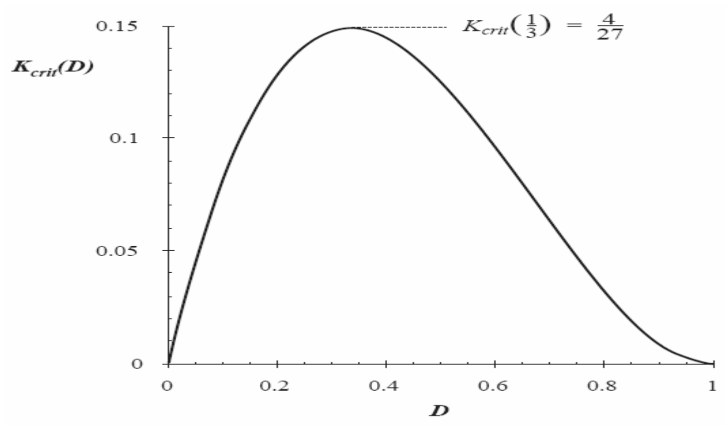

Figure 10 Boost converter K_{crit}(D) versus D.

Figure10 illustrates what happens when K is less than 4/27. The converter then operates in the discontinuous conduction mode for some intermediate range values of D near D = 1/3 [7]. But the converter operates in continuous conduction mode near D = 0 and D = 1. The boost converter must operate in the continuous conduction mode near D = 0 because the ripple magnitude approaches zero while the dc component I does not [7].

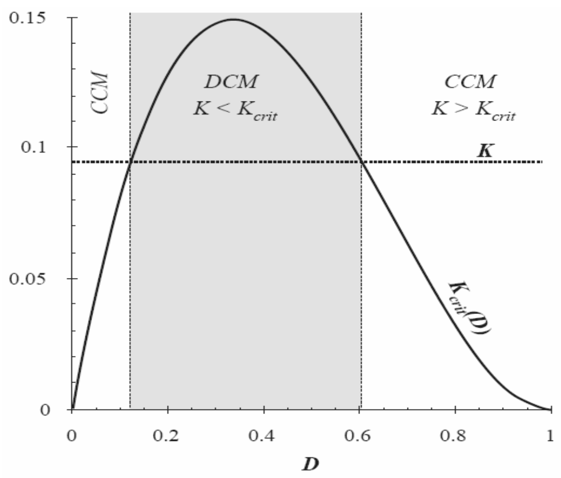

Figure 11 Comparison of K with K_{crit}(D).

CHAPTER 2

THE SMALL SIGNAL APPROXIMATION

2.1 Overview

The main objective of this approximation is to maintain the converter output voltage v(t) equal to an accurate, constant value V. This assumption is very useful for basic converter modeling. Before starting to explain the approximation, some general knowledge will be given [7].

While modeling the converter in steady-state region, it is assumed that there is no change in the input voltage and load [7]. A constant duty cycle is applied to the switch and an output voltage (with a ripple in accordance with design) will be generated on the load [7]. But, when controlling a converter, there are always some disturbances which generate uncertainities [7]. These disturbances can be in the:

• Input voltage, $v_g(t)$, and/or

• Load, R

These disturbances bring difficulty to create the dynamic model of a converter. Steady-state model of the converter can be determined as described before, but the assumptions given in steady-state analysis section are not sufficient to develop the dynamic model of the converter that will represent the characteristics of the converter in transient conditions. This dynamic model is also needed to model converter controller (details about the controller design using small-signal analysis will be given later).

As a summary, small signal approximation is a method that helps the designer to model the dynamics of the converter.

There are some steps to obtain the small signal model of a converter. The next sections will give some detail for boost converter small-signal modeling.

2.2 Neglecting the Switching Ripple

The duty cycle is modulated sinusoidally. So duty cycle expression is given as [7]:

$$d(t) = D + Dm \cos w_m t$$

where D and Dm are constants, $| D_m | << D$, and the modulation frequency w_m is much smaller than the converter switching frequency w_s. Figure 12 shows the resulting variations in transistor gate drive signal and converter output voltage [7]:

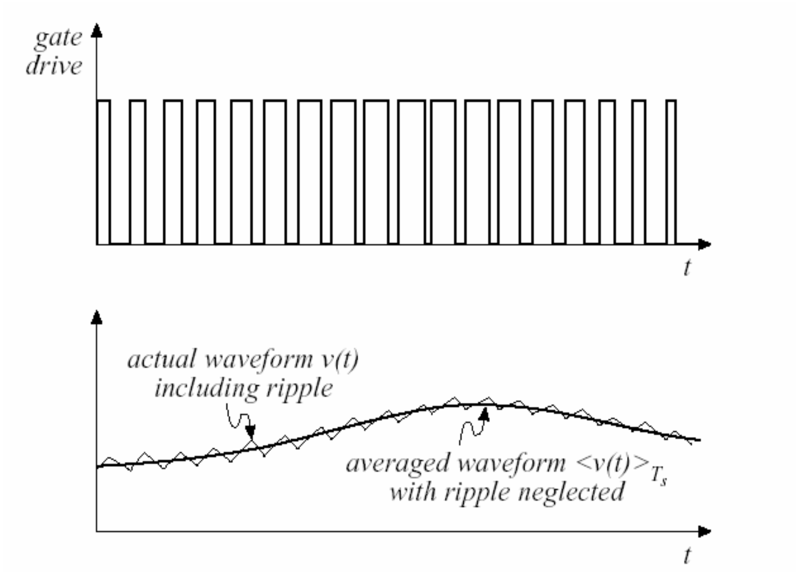

Figure 12 Variations in transistor gate drive signal and converter output voltage.

In accordance with the gate driver signal (duty cycle) change, the output voltage is also changed with ripple on itself. Notice that the average of the ac ripple signal is equal to zero in one switching cycle [7]. This ac ripple signal is on a dc (or averaged) signal that describes the main objective of the small signal assumption. It is clearly seen that when the small ac ripple is neglected, a dc (or averaged) signal that will simplify the dynamic modeling of a converter will remain.

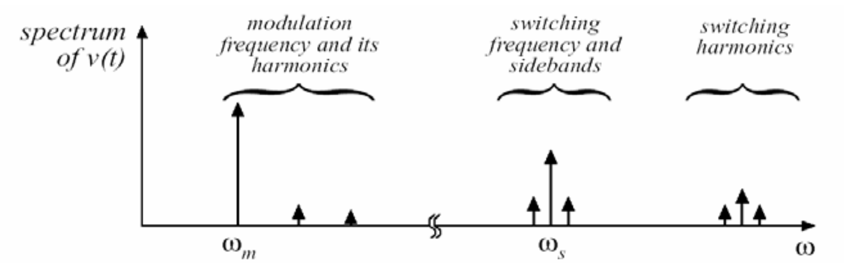

Figure 13 Frequency spectrum of output voltage [7].

Figure 13 shows the frequency spectrum of output voltage. It is seen that this spectrum contains frequency components at:

• Modulation frequency and its harmonics [7]

• Switching frequency and its harmonics [7]

• Sidebands of switching frequency [7]

It is clear that with small switching ripple and high frequency components (switching harmonics and sidebands) are small. If this ripple is neglected, then only low frequency components (modulation frequency and harmonics) remain [7].

The main objective of ac converter modeling is the prediction of how low-frequency variations in duty cycle induce low frequency variations in the converter voltages and currents [7]. To achieve this objective, small signal modeling ignores the switching ripple, complicated switching harmonics and sidebands [7]. The main approach is removing switching harmonics by averaging all waveforms over one switching period.

Average of a signal (named as “x”) over one switching period is given as [7]:

$$\left\langle x_L(t) \right\rangle_{T_S} = \frac{1}{T_S} \int_{t}^{t+T_S} x(\tau) d\tau$$

where T_s is the period of the signal. In converter applications, average of inductor current and capacitor voltage over one switching period in converter also is given as below [7]:

$$L \frac{d\left\langle i_L(t) \right\rangle_{Ts}}{dt} = \left\langle v_L(t) \right\rangle_{Ts}$$

$$C \frac{d\left\langle v_C(t) \right\rangle_{Ts}}{dt} = \left\langle i_C(t) \right\rangle_{Ts}$$

Notice that, in steady state, inductor voltage and capacitor current are equal to zero by inductor volt-second balance and capacitor charge balance. So the following equations are given:

$$\left\langle v_L(t) \right\rangle_{Ts} = 0$$

$$\left\langle i_C(t) \right\rangle_{Ts} = 0$$

The averaged voltages and currents are, in general, nonlinear functions of the converter duty cycle, voltages, and currents [7]. Hence, the averaged equations constitute a system of nonlinear differential equations. Hence, linearizing is must by constructing a small-signal converter model.

Figure 14 shows the nonlinear static control-to-output characteristic of a boost converter. It is seen that linearizing is done at a quiescent point that is over the static control-to-output curve (for example at duty cycle = 0.5) [7]. The reason to select a converter operating point is that the converter has different characteristics (for example voltage and current ripples) at different operating points. Ripple values on the output voltage of the converter on two different duty cycles are differing from each other. So to be able to apply the small-signal analysis to a converter, it is essential to select an operating point in which one desires to operate the converter. In the following section it will be noticed that small-signal transfer functions of converters have duty cycle ("D") parameters in their formulas. This is the duty cycle of the controller in steady state region. So determination of the operating point is essential for exact modeling and wrong desicion will affect model operation (especially in control design).

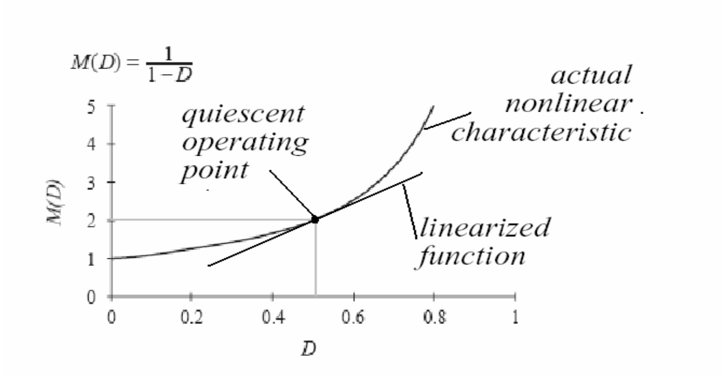

Figure 14 Nonlinear static control-to-output characteristic of a boost converter.

2.3 Boost Converter Small-Signal Modeling in DCM of Operation

The average large-signal model of the general two-switch network in the DCM is represented in the following figure[7].

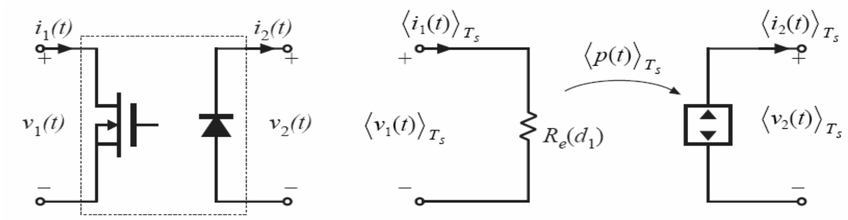

Figure 15 (a) The general two-switch network and (b) corresponding averaged switch model in the discontinuous conduction mode.

In this model the input port behaves as resistance R_e. The R_e value is:

$$R_e = \frac{2L}{d^2 T_S}$$

The Boost converter then reduces to the following circuit:

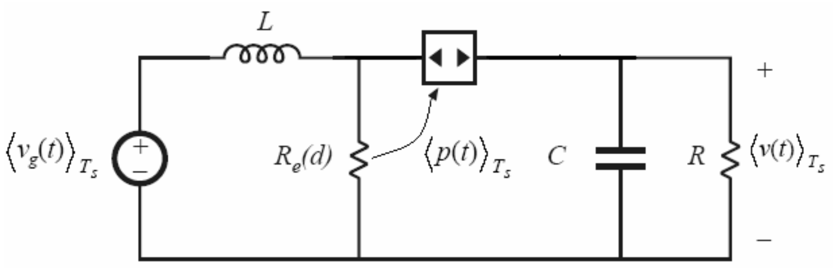

Figure 16 Averaged large-signal equivalent circuit of the Boost converter operating in the discontinuous conduction mode.

In the large-signal ac equivalent circuit the averaged switch models are nonlinear. Hence, loss-free resistor is linearized and perturbed to construct small-signal ac model. So the small-signal switch model is:

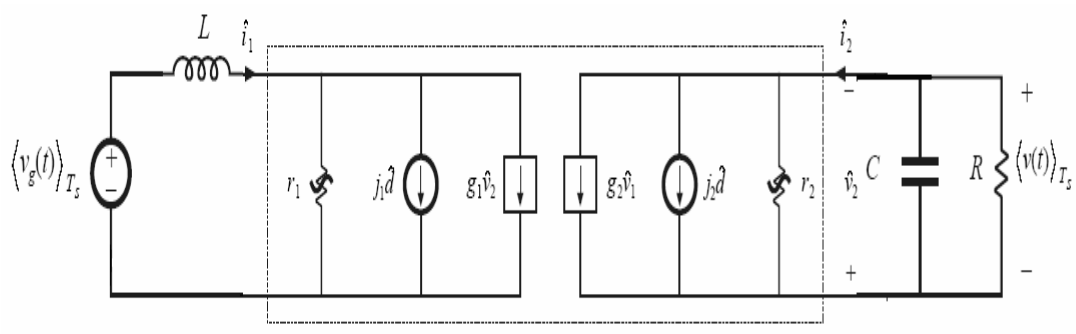

Figure 17 Averaged small-signal model of the switch network boost converter.

where:

$$g_1 = \frac{1}{(M-1)^2 R_e} \quad , \quad g_2 = \frac{2M-1}{(M-1)^2 R_e}$$

$$j_1 = \frac{2MV_1}{D(M-1)R_e} \quad , \quad j_2 = \frac{2V_1}{D(M-1)R_e}$$

$$r_1 = \frac{(M-1)^2}{M^2} R_e \quad , \quad r_e = (M-1)^2 R_e$$

2.4 Boost Converter Transfer Functions

When designing a dc-dc converter, it is always desired that the output of the converter (output current and output voltage) is consistent with the design inputs [7]. The converter outputs are the affected parameters while the duty cycle, input voltage, input impedence and load are the reason of the converter outputs changes [7].

The first is line-to-output transfer function. The line-to-output transfer function $G_{vg}(s)$ is found by setting duty cycle variations d(s) to zero, and then solving for the transfer function from $v_g(s)$ to v(s) [7]:

$$G_{vg}(s) = \left. \frac{\hat{v}(s)}{\hat{v}_g(s)} \right|_{\hat{d}(s)=0}$$

This transfer function describes how variations or disturbances in the applied input voltage $v_g(t)$ lead to disturbances in the output voltage v(t) [7]. The transfer function $G_{vg}(s)$ is used to determine the effect of these harmonics on the converter output voltage v(t) [7].

The control-to-output transfer function $G_{vd}(s)$ is found by setting the input voltage variations $v_g(s)$ to zero, and then solving the equivalent circuit model for v(s) as a function of d(s) [7]:

$$G_{vd}(s) = \left. \frac{\hat{v}(s)}{\hat{d}(s)} \right|_{\hat{v}_g(s)=0}$$

This transfer function describes how control input variations d(s) influence the output voltage v(s) [7]. In an output voltage regulator system, $G_{vd}(s)$ is a key component of the loop gain and has a significant effect on regulator performance.

Another factor that influences the converter design is the output impedance. The output impedance $Z_{out}(s)$ is found under the conditions that $v_g(s)$ and d(s) variations are set to zero. $Z_{out}(s)$ describes how variations in the load current affect the output voltage [7]. This quantity is also important in voltage regulator design [7]. It may be appropriate to define $Z_{out}(s)$ either including or not including the load resistance R.

In this thesis, input impedance is assumed infinitive and there is no change in load and input voltage, G_{vg}, Z_{in} and Z_{out} are ignored. The main objective of this thesis is to demonstrate how output voltage is affected by ac changes in duty cycle and how a stable control can be achieved.

The converter contains two independent ac inputs: the control input d(s) and the line input $v_g(s)$ [7]. The ac output voltage variations v(s) are expressed as the superposition of terms arising from these two inputs [7]:

$$\hat{v}(s) = G_{vd}(s)\hat{d}(s) + G_{vg}(s)\hat{v}_g(s)$$

Hence, the transfer functions $G_{vd}(s)$ and $G_{vg}(s)$ are defined as [7]:

$$G_{vd}(s) = \left.\frac{\hat{v}(s)}{\hat{d}(s)}\right|_{\hat{v}_g(s)=0} \qquad \text{and} \qquad G_{vg}(s) = \left.\frac{\hat{v}(s)}{\hat{v}_g(s)}\right|_{\hat{d}(s)=0}$$

For boost converter;

$$G_{vd} = \frac{G_{do}}{1+\frac{s}{w_p}} \quad \text{and} \quad G_{vg} = \frac{G_{go}}{1+\frac{s}{w_p}}$$

where:

$$G_{do} = \frac{2V}{D}\frac{M-1}{2M-1} \quad , \qquad G_{go} = M \quad , \quad w_p = \frac{2M-1}{(M-1)RC}$$

CHAPTER 3

CONTROLLER DESIGN

3.1 Overview

Output voltage of a switching converter depends on duty cycle d, input voltage v_g, and load current i_{load} (or output impedance), which is represented as in

Figure **18** [7].

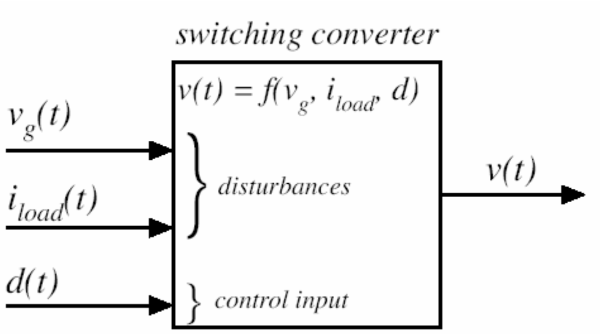

Figure 18 Output voltage of a switching converter depends on duty cycle d, input voltage v_g, and load current i_{load} .

The main objective of the controller is to maintain constant output voltage v(t) = V, in spite of disturbances in $v_g(t)$ and $i_{load}(t)$ [7].

So for converters it is not expected to set the duty cycle to a single value, and obtain a given constant output voltage under all conditions. Negative feedback is building a circuit that automatically adjusts the duty cycle as necessary, to obtain the specified output voltage with high accuracy, regardless of disturbances or component tolerances [7].

A general control scheme of a converter is given in

Figure **19** [7]:

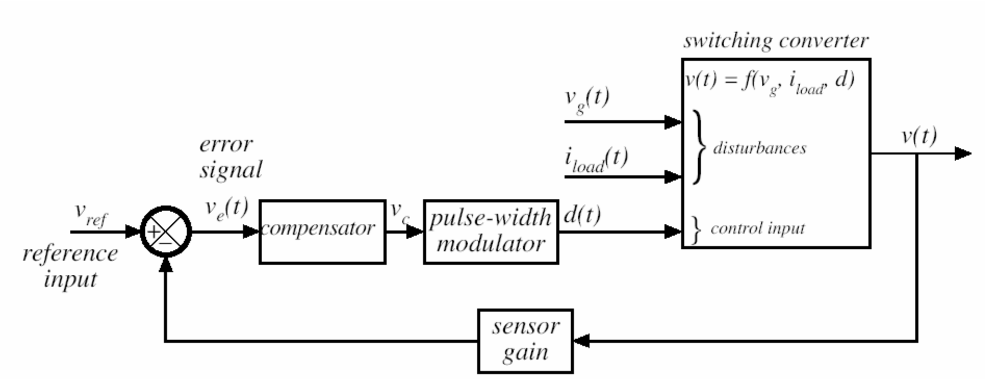

Figure 19 General control sheme of a converter.

Output voltage is expressed as [7]:

$$\hat{v}(s) = G_{vd}(s)\hat{d}(s) + G_{vg}(s)\hat{v}_g(s) \pm Z_{out}(s)\hat{i}_{load}(s)$$

where:

$$G_{vd}(s) = \left. \frac{\hat{v}(s)}{\hat{d}(s)} \right|_{\substack{\hat{v}_g = 0 \\ \hat{i}_{load} = 0}} \qquad G_{vg}(s) = \left. \frac{\hat{v}(s)}{\hat{v}_g(s)} \right|_{\substack{\hat{d} = 0 \\ \hat{i}_{load} = 0}} \qquad Z_{out}(s) = \pm \left. \frac{\hat{v}(s)}{\hat{i}_{load}(s)} \right|_{\substack{\hat{d} = 0 \\ \hat{v}_g = 0}}$$

First off all, the signal of the feedback loop is perturbed and linearized as in the small signal modeling [7]. This means, for example:

$$v_{ref}(t) = V_{ref} + \hat{v}_{ref}(t)$$

$$v_e(t) = V_e + \hat{v}_e(t)$$

It is known that the first term at the right side of the equations represents the dc constants (at operating point), the second is for the ac component of the related signal [7]. It should be remembered that the aim is to determine the effect of the ac change on the converter operation. So the ac equivalent scheme of a converter controller is given as in Figure 20 [7]:

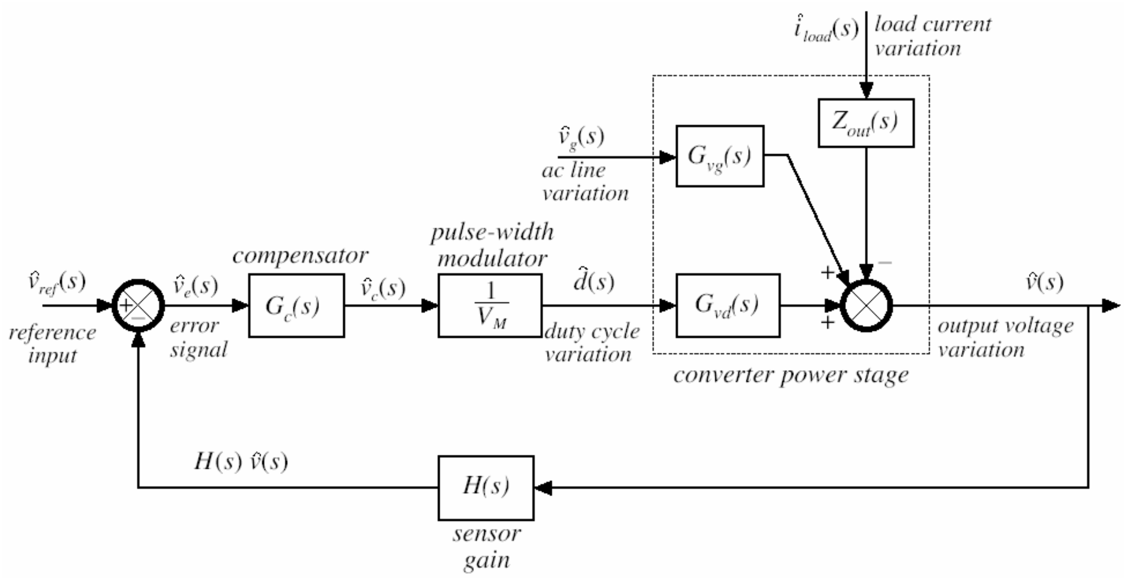

Figure 20 AC equivalent scheme of a converter controller.

By manipulating block diagram to solve for v(s), the following is obtained [7]:

$$\hat{v} = \hat{v}_{ref} \frac{G_c G_{vd} / V_M}{1 + HG_c G_{vd} / V_M} + \hat{v}_g \frac{G_{vg}}{1 + HG_c G_{vd} / V_M} \pm \hat{i}_{load} \frac{Z_{out}}{1 + HG_c G_{vd} / V_M}$$

which is of the form:

$$\hat{v} = \hat{v}_{ref} \frac{1}{H} \frac{T}{1+T} + \hat{v}_g \frac{G_{vg}}{1+T} \pm \hat{i}_{load} \frac{Z_{out}}{1+T}$$

With

$$T(s) = H(s) G_c(s) G_{vd}(s) / V_M = \text{"}\textit{loop gain.}\text{"}$$

Loop gain T(s) is equal to product of the gains around the negative feedback loop. Original (open-loop) line-to-output transfer function is [7]:

$$G_{vg}(s) = \left. \frac{\hat{v}(s)}{\hat{v}_g(s)} \right|_{\substack{\hat{d}=0 \\ \hat{i}_{load}=0}}$$

With addition of negative feedback, the line-to-output transfer function becomes [7]:

$$\left.\frac{\hat{v}(s)}{\hat{v}_g(s)}\right|_{\substack{\hat{v}_{ref}=0\\ \hat{i}_{load}=0}} = \frac{G_{vg}(s)}{1+T(s)}$$

So, feedback reduces the line-to-output transfer function by a factor of [7]:

$$\frac{1}{1+T(s)}$$

So, it is clear that, if T(s) is large in magnitude, then the line-to-output transfer function becomes small [7]. This means that the ac variation on the input voltage will not affect the output, which is a desired condition in converter applications [7].

Original (open-loop) output impedance is [7]:

$$Z_{out}(s) = \pm \left.\frac{\hat{v}(s)}{\hat{i}_{load}(s)}\right|_{\substack{\hat{d}=0\\ \hat{v}_g=0}}$$

With addition of negative feedback, the output impedance becomes [7]:

$$\left.\frac{\hat{v}(s)}{\pm\hat{i}_{load}(s)}\right|_{\substack{\hat{v}_{ref}=0\\ \hat{v}_g=0}} = \frac{Z_{out}(s)}{1+T(s)}$$

Feedback reduces the output impedance by a factor of [7]:

$$\frac{1}{1+T(s)}$$

So, it is clear that, if T(s) is large in magnitude, then the output impedance is greatly reduced in magnitude [7]. This means that the load variation will not affect the output, which is a desired condition in converter applications [7].

Closed-loop transfer function from v(s) to V_{ref} is [7]:

$$\left.\frac{\hat{v}(s)}{\hat{v}_{ref}(s)}\right|_{\substack{\hat{v}_g=0\\ \hat{i}_{load}=0}} = \frac{1}{H(s)}\frac{T(s)}{1+T(s)}$$

If the loop gain is large in magnitude, i.e., || T || >> 1, then (1 + T) = T and T/(1 + T) = T/T = 1. The transfer function then becomes [7]:

$$\frac{\hat{v}(s)}{\hat{v}_{ref}(s)} \approx \frac{1}{H(s)}$$

which is independent of the gains in the forward path of the loop. This result applies equally well to dc values [7]:

$$\frac{V}{V_{ref}} = \frac{1}{H(0)}\frac{T(0)}{1+T(0)} \approx \frac{1}{H(0)}$$

This means that a reference signal is applied to the controller, the output of the converter will be only the desired value which is equal to the reference signal product by sensor gain, which is a desired condition in converter applications [7].

In controller design, the "T" gain has importance to determine the necessary control parameters. The next are for the different characteristics of the reference-to-output transfer functions that are dependent on this "T" gain.

$$\frac{T}{1+T} \approx \begin{cases} 1 & \text{for } \| T \| >> 1 \\ T & \text{for } \| T \| << 1 \end{cases}$$

$$\frac{1}{1+T(s)} \approx \begin{cases} \dfrac{1}{T(s)} & \text{for } \| T \| >> 1 \\ 1 & \text{for } \| T \| << 1 \end{cases}$$

The following Bode diagram (Figure 21) is given only to show the characteristics of the gain "T" and "T/(1 + T)" at different frequencies [7].

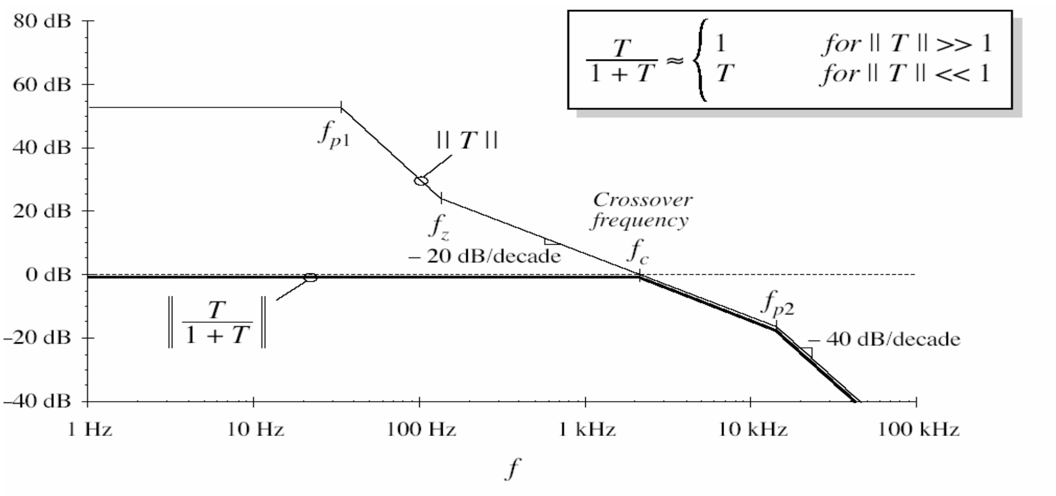

Figure 21 Characteristics of the gain "T" and "T/(1+T)" at different frequencies.

At frequencies sufficiently less that the crossover frequency, the loop gain T(s) has large magnitude [7]. The transfer function from the reference to the output becomes:

$$\frac{\hat{v}(s)}{\hat{v}_{ref}(s)} = \frac{1}{H(s)}\frac{T(s)}{1+T(s)} \approx \frac{1}{H(s)}$$

This is the desired behavior: the output follows the reference according to the ideal gain 1/H(s). The feedback loop works well at frequencies where the loop gain T(s) has large magnitude [7]. At frequencies above the crossover frequency, || T || < 1. The quantity T/(1 + T) then has a magnitude approximately equal to 1, and is obtained as [7]:

$$\frac{\hat{v}(s)}{\hat{v}_{ref}(s)} = \frac{1}{H(s)}\frac{T(s)}{1+T(s)} \approx \frac{T(s)}{H(s)} = \frac{G_c(s)G_{vd}(s)}{V_M}$$

This coincides with the open-loop transfer function from the reference to the output. At frequencies where || T || < 1, the loop has essentially no effect on the transfer function from the reference to the output [7]. Below the crossover frequency: f < fc and || T || >1 . Then 1/(1 + T) = 1/T, and disturbances are reduced in magnitude by 1/|| T ||. Above the crossover frequency: f > fc and || T || < 1. Then 1/(1 + T) = 1, and the feedback loop has essentially no effect on disturbances [7]. This situation is summarized below:

$$\frac{1}{1+T(s)} \approx \begin{cases} \dfrac{1}{T(s)} & for \; \| T \| >> 1 \\ 1 & for \; \| T \| << 1 \end{cases}$$

3.2 Stability Criteria

Original transfer functions, before introduction of feedback ("open-loop transfer functions") are [7]:

$$G_{vd}(s) \qquad G_{vg}(s) \qquad Z_{out}(s)$$

Upon introduction of feedback, these transfer functions become ("closed-loop transfer functions") [7]:

$$\frac{1}{H(s)}\frac{T(s)}{1+T(s)} \qquad \frac{G_{vg}(s)}{1+T(s)} \qquad \frac{Z_{out}(s)}{1+T(s)}$$

Even though the original open-loop system is stable, the closed-loop transfer functions can be unstable and contain right half-plane poles [7]. Even when the closed-loop system is stable, the transient response can exhibit undesirable ringing and overshoot, due to the high Q -factor of the closed-loop poles in the vicinity of the crossover frequency [7]. When feedback destabilizes the system, the denominator (1 + T(s)) terms in the closed-loop transfer functions contain roots in the right half-plane (i.e., with positive real parts) [7]. For stability investigation, phase margin test method is very easy for converter controller design [7].

3.2.1 The Phase Margin Test

This test on T(s) is to determine whether 1/(1 + T(s)) contains RHP poles. The crossover frequency f_c is defined as the frequency where [7]:

$$\left\| T(j2\pi f_C) \right\| = 1 \Rightarrow 0\text{dB}$$

The phase margin φ_m is determined from the phase of T(s) at f_c, as follows [7]:

$$\varphi_m = 180^0 + \angle T(j2\pi f_C)$$

If there is exactly one crossover frequency, and if T(s) contains no RHP poles, then the quantities T(s)/(1 + T(s)) and 1/(1 + T(s)) contain no RHP poles whenever the phase margin is positive [7].

Figure **22** is an example to show the stability and/or phase margin.

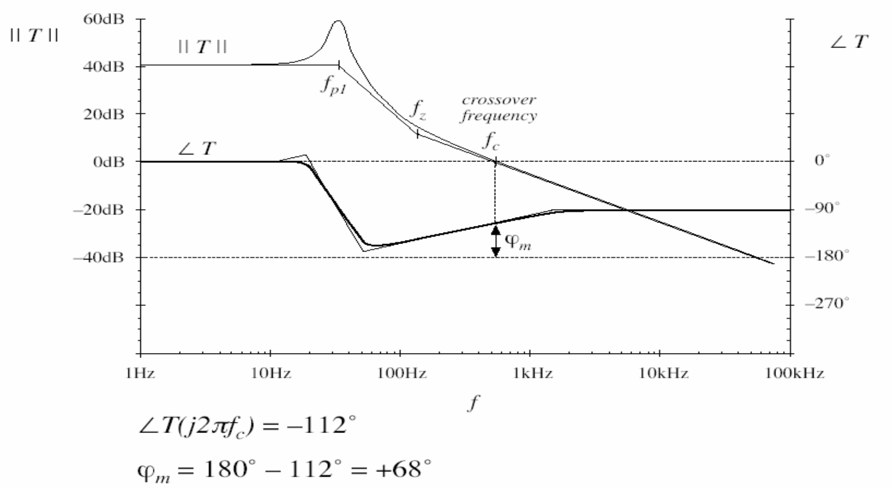

Figure 22 A Bode plot example to show the phase margin (stable).

The following figure is an example to show the unstability.

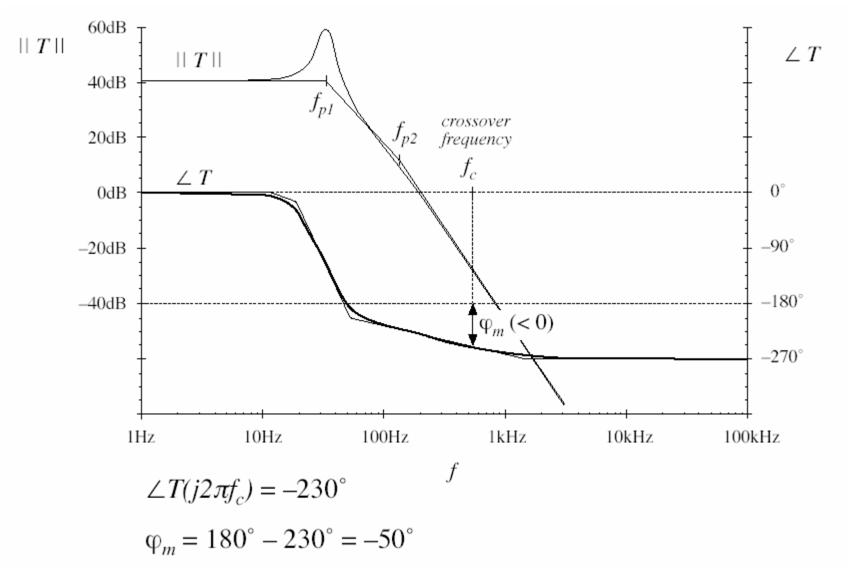

Figure 23 A Bode plot example to show the phase margin (unstable).

The phase margin also measures the system's tolerance to time delay [9]. The time delay is thought of as an extra block in the forward path of the block diagram that adds phase to the system but has no effect on the gain [9].

Generally, the delay in converters' output is caused by internal resistances, current limits and capacitances within the converter. This delay causes a phase difference between the converter's input and output signals. If there are enough stages in the converter, at some frequency, the output signal will lag the input signal by one wavelength (in this situation, the converter's output signal will be in phase with its input signal though lagging it by 360°). Such a situation will cause problems in converter control that use "negative feedback". Negative feedback is a process of feeding back to the input a part of a system's output, so as to reverse the direction of change of the output. This tends to keep the output from changing, and it is stabilizing and attempts to maintain constant conditions. So, the converter output voltage will oscillate if the fed-back output signal is in phase with the input signal (output signal lagging behind input signal by 360°). The oscillation will occur because the fed-back output signals will then re-inforce the input signal at that frequency. In dc-dc converters, the critical output phase angle is -180° because the output is negatively fed back to the input, which adds an additional -180°.

As a summary, a larger phase margin is better, in terms of stability [9]. A negative phase margin means that the system is unstable [9].

3.3 Compensator Design

Typical key points for regulator design can be given as below:

- Effect of load current variations on output voltage regulation
- Effect of input voltage variations on the output voltage regulation
- Transient response time
- Overshoot and ringing

During design, all of the specifications given below are crucial. After the first design is completed, there may exist some problems related with the issue given above. To solve regulator design problem, add compensator network $G_c(s)$ can be added to modify T(s) in order to meet all the specifications [7].

There are three types of compensators that are usually used in converter applications. They are:

- Proportional-plus-integral (PI): used for low frequency gain improvement.
- Proportional-plus-derivative (PD): used for phase margin improvement.
- Proportional-plus-integral-plus-derivative (PID): used for low frequency gain and phase margin improvement.

In this thesis, PI compensator is used as a compensator. An integral controller (Ki) decreases the rise time, increases both the overshoot and the settling time, and eliminates the steady-state error. In chapter 5, an op-amp circuitry will be presented as PI compensator. In chapter 6, Bode diagram and related transfer function of the designed PI compensator will be given.

CHAPTER 4

MATLAB GUI

4.1 Overview

A graphical user interface (GUI) is a graphical display that contains devices, or components, that enable a user to perform interactive tasks [8]. To perform these tasks, the user of the GUI does not have to create a script or type commands at the command line [8]. Often, the user does not have to know the details of the task at hand [8].
The GUI components can be menus, toolbars, push buttons, radio buttons, list boxes, and sliders [8]. In MATLAB, a GUI can also display data as plots, and can group related components [8].

- **GUIDE**

GUIDE, the MATLAB graphical user interface development environment, provides a set of tools for creating graphical user interfaces (GUIs) [8]. These tools simplify the process of laying out and programming GUIs [8].

- **Laying Out A GUI**

The GUIDE Layout Editor enables the user to populate a GUI by clicking and dragging GUI components -- such as buttons, text fields, sliders, axes, and so on -- into the layout area [8]. It also enables the user to create menus and context menus for the GUI [8].

- **Programming the GUI**

When saving GUI layout, GUIDE automatically generates an M-file that the user can use to control how the GUI works [8]. This M-file provides codes to initialize the GUI and contains a framework for the GUI callbacks - the routines that execute in response to user-generated events such as a mouse click [8]. Using the M-file editor, the user can add code to the callbacks to perform the functions wanted [8].

4.2 "Converter Design" GUI

In MATLAB Workspace, by typing "Converter_Design" GUI will be opened (

Figure 24). This guide will help the user to design the converter, obtain small signal model, frequency responses, closed loop/open loop transfer functions and run simulations using MATLAB-Simulink. An instruction related with GUI is given in this section. In the next chapter, there is an example that shows the usage of GUI for boost converter design and obtained results. Before starting, the following "Notes" have to be read. They include crucial information to be known before starting to use GUI.

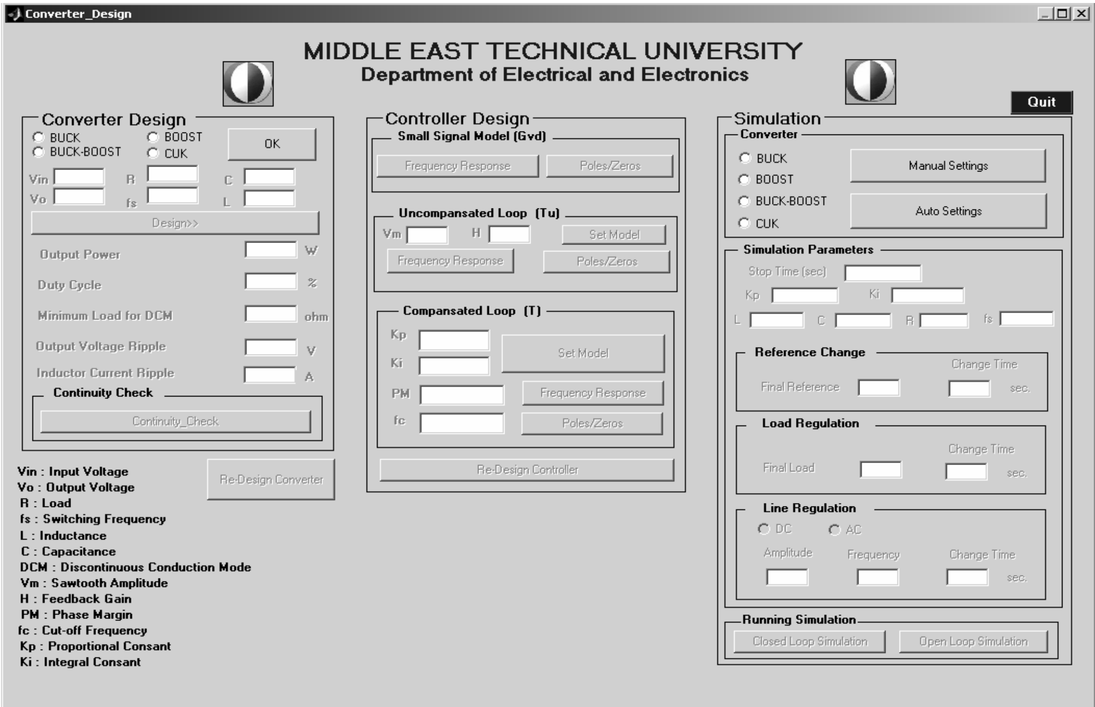

Figure 24 “”Converter Design” GUI.

Note-1: All actions can be performed by pressing button on the GUI. GUI is designed in a hierarchic structure that enables the user to pass to the right step by enabling-disabling the other buttons on the screen.

Note-2: “Reset” buttons are used to end the application and return to the starting. “Re-design” button enables the user to return to the previous step for any undesired condition occuring in data entry to the GUI.

Note-3: All figures will be closed when the GUI is ended and reset for starting.

Note-4: “Set Model” buttons are used to generate the related transfer functions.

Note-5: If the user does not select a converter type and presses “OK” and/or “Press” button, “Buck” converter will be automatically selected

Note-6: GUI uses M-files to perform some specific operations when the user presses to a button or checks a radio box. An M-file consists of special MATLAB codes for special operation. In this thesis, five different M-files are used for different purposes. These files and their brief descriptions are given below:

- **Converter_Design.m**: This is the main M-file used directly by GUI. All of the other M-files are called in this main M-file. All of the functionalities are provided by it. For example, what it will occur when a button is pressed or which figure will be plotted etc. are defined in this main M-file. It has no codes that directly affect the design/control of the converters, but it calls the other M-files, run them and uses the outputs to organize the GUI.
- **Design.m:** This M-file gets design inputs and generates minimum load for discontinuity, output voltage ripple, switching duty cycle and output real power.
- **Continuity.m**: This M-file determines the conduction mode of the designed converter.
- **O_trans_func.m:** This M-file gets design outputs and generates converter transfer function G_{vd} by using small-signal equations.
- **PI.m:** This M-file gets converter transfer function G_{vd}, sawtooth control signal magnitude V_m and feedback gain H in closed-loop control applications and generates firstly uncompensated converter transfer function T_u. Then it gets uncompensated converter transfer function T_u, proportional gain K_p and integral gain K_i and generated compensated converter transfer function T by using small-signal equations.

These M-files are copied in CD as attachment.

Note-7: “Frequency Response” and “Poles/Zeroes” buttons will return to passive when they are pressed. So for user future observation, they are not to be closed during the application.

The following GUI special sections are given to provide general information about usage.

Converter Type: Converter type is selected in this section. The type shall be one of those given below:

- Buck Converter
- Boost Converter
- Buck-Boost Converter
- Cuk Converter

One of the converter types should be selected to be able to pass to the other steps.

Design Inputs: They are needed to design the converter design outputs. They are:

- V_{in} (Converter Input Voltage)
- V_o (Converter Output Voltage)
- R (Load)
- f_s (Switching Frequency)
- L (Inductance)
- C (Capacitance)

Design Outputs: Design outputs are calculated by GUI in accordance with the design inputs specified before. This step is performed by pressing “Design” button. This button activates “design.m” M-file that contains steady-state design formulas of the related converter. The design outputs are:

- Output Power
- Duty Cycle
- Minimum Load for Discontinuity
- Output Voltage Ripple
- Inductor Current Ripple

Continuity Checking: This step is used to control whether the designed converter is in continuous conduction mode or not.

Models: Some models are generated to be able to generate PI compensator parameters in closed-loop control. They are:

- **Small-Signal Model (G_{vd}):** Transfer function between duty cycle and converter output voltage.
- **Uncompensated Loop Model (T_u)**: Closed-loop transfer function with no compensation
- **Compensated Loop Model (T):** Closed-loop transfer function with compensation

Each model has its special section on the GUI. The related plots of the models can be generated by pressing "Frequency Response" and "Poles/Zeroes" buttons placed in these special sections.

Frequency Response: "Frequency Response" buttons are used for easy investigation of the related transfer function frequency response by the user. Which transfer function frequency response the user is investigating can be seen under the name of the related section. By pressing "Frequency Response" button, the user can view phase and gain margins, cut-off frequency and low/high frequency characteristics of the related model. On the generated figure, the user can select a point by using the cursor. The related frequency and magnitude/phase can be seen on the screen.

"Frequency Response" figures that can be generated are listed below:

- Frequency Response for Small-Signal Model (G_{vd})
- Frequency Response for Uncompensated Loop Model (T_u)
- Frequency Response for Compensated Loop Model (T)

Another "Frequency Response" plot is generated during design stages. This is generated when one of the "Frequency Response" buttons on the GUI is pressed. Its main function is to plot all the frequency responses generated during design on a single figure. It is very useful for the user to see what actions are performed at the end of the design.

Poles/Zeroes: “Poles/Zeroes” buttons are used for easy investigation of the related transfer functions’ poles and zeroes by user. Which transfer functions’ poles and zeroes the user is investigating can be seen under the name of the related section. When these buttons are pressed, a “Pole-Zero map” appears on the screen. On the map, the user can see all poles and zeroes and make point selection by the cursor. The related poles and zeroes values (real and imaginary parts) can be seen on the screen.

“Poles/Zeroes” figures (maps) that can be generated are listed below:

- Poles/Zeroes for Small-Signal Model (G_{vd})
- Poles/Zeroes for Uncompensated Loop Model (T_u)
- Poles/Zeroes for Compensated Loop Model (T)

Compensator Inputs: Some design inputs are needed to calculate a specific compensator for “T_u” (Uncompensated Loop Model). They are:

- **Vm** : Amplitude of the sawtooth control signal.
- **H** : Feedback gain.

Controller Inputs: Some design inputs are needed to calculate specific compensator parameters for “T” (Compensated Loop Model). They are:

- K_p: Proportional Gain
- K_i: Integral Gain

PI Compensator Parameters: PI compensator parameters are calculated automatically in accordance with the user controller inputs. They are:

- PM: Phase Margin
- f_c: Cut-off Frequency

Converter Simulation: By using “Auto Setting” and “Manual Setting” options, the user can simulate the designed converter type with MATLAB-Simulink. “Auto

Setting” button is used to transmit all calculated design parameters to the simulation program. “Manual Setting” button is for manual regulation. The user can run another converter simulation after one is terminated either manually or automatically.

Quit: “Quit” button is the only way to quit the application.

CHAPTER 5

HARDWARE DESCRIPTION

5.1 Overview

The general view of the boost converter test box is given in Figure 25. It contains open and closed loop control buttons and probes for external measurements. The functions of each section are shown in Figure 25.

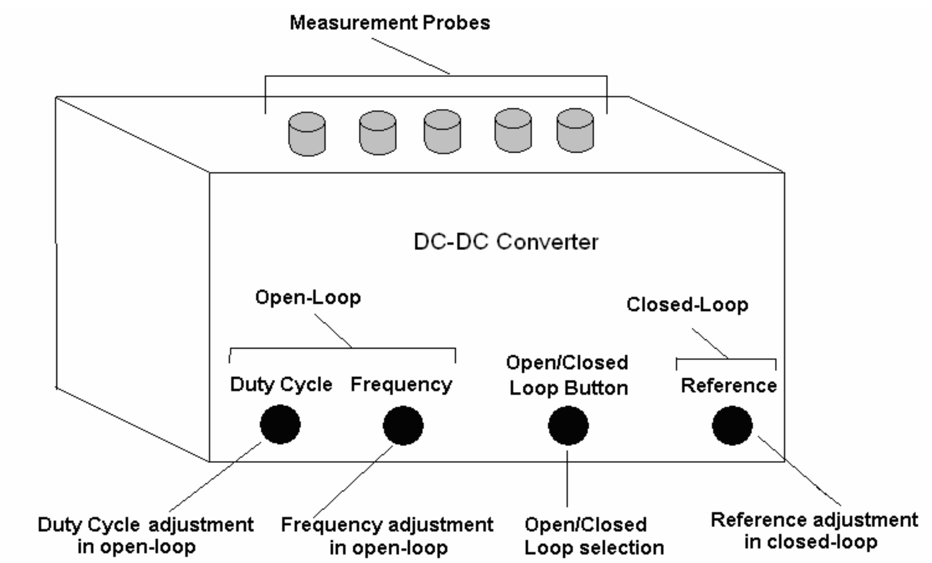

Figure 25 General view of the dc-dc converter test box.

The specification of the boost converter test box is given in Table 1.

Table 1 Boost converter test box specification

Input voltage	10 V-30 V
Minimum Output Load	30 Ω
Inductor	220 µH ($R_{internal}$ = 0.05Ω)
Capacitor	100 µF (ESR = 0.15)
Operation Frequency	7.7 kHz - 58 kHz
Maximum Duty Cycle	70 %

The general block diagram of the circuit is shown in Figure 26. The circuit consists of three parts: power stage, PWM stage and compensator stage.

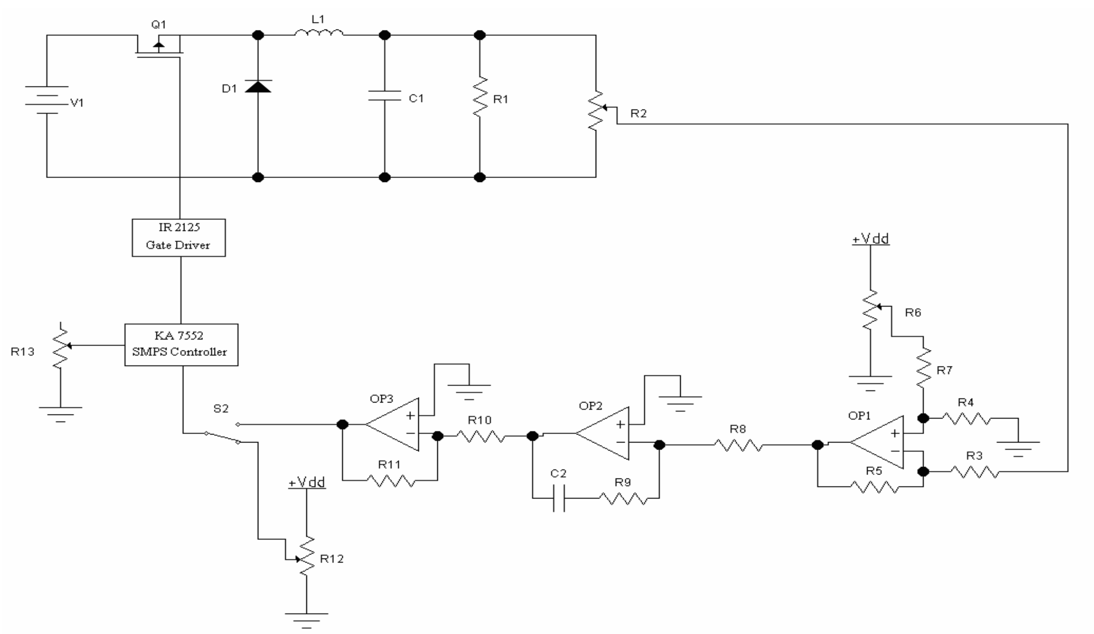

Figure 26 Hardware overview

The power stage consists of a boost converter and IR2125 gate driver. In the conpensator stage op-amps are used to design PI controller. In the PWM stage KA7552 IC is used to produce PWM signals.

In the power stage the input voltage is adjustable up to 30 V. The inductor is constant and has the value of 220 μH; also the capacitor is constant and is 100 μF. The minimum load connected to the output should not be smaller than 30 Ω for safety.

In the compensator stage OP1 is the difference amplifier. The reference voltage that is adjusted with R_6 is extracted from output voltage that is scaled with R_2. OP2 opamp is used as PI compensator. The transfer function of compensator is:

$$G(s) = -\frac{R_9}{R_8}\frac{\left(R_9 C_2 s + 1\right)}{R_9 C_2 s}$$

From this equation the PI parameters are:

$$Kp = \frac{R_9}{R_8} \qquad , \qquad Ki = \frac{1}{R_8 C_2}$$

In this thesis

$K_p = 7.35$
$K_i = 890$
$R_8 = 8258\Omega$
$R_9 = 1123\ \Omega$
$C_2 = 1\ \mu F$

Because a negative voltage level is obtained at the output of "OP2" opamp, another opamp, "OP3" is used as an inverting amplifier which has "$-R_{11}/R_{10}$" convertion ratio.
S2 switch selects the operation of the circuit, if it is in position connected to the OP3 output the circuit operates in closed loop operation, if it is in position connected to the R_{12} the circuit operates in open loop operation. R_{12} adjusts the duty cycle of the PWM output in the open loop operation. R_{13} adjusts the frequency of the PWM, the frequency is adjustable both in the open loop and closed loop operations.

As gate driver in the circuit IR 2125 is used. It is a high side gate driver that can be used in the low side applications. This driver also has the cycle-by-cycle over current protection feature. The over current protection circuit is shown in Figure 27.

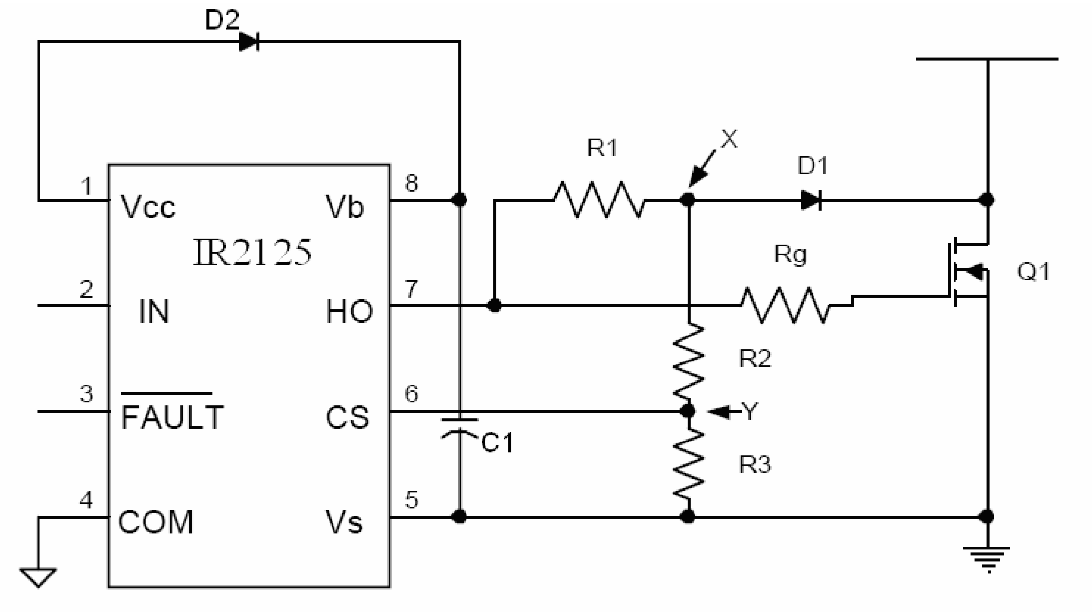

Figure 27 Current sensing circuit configuration.

In the circuit C_1 and D_2 are bootstrap capacitor and bootstrap diode, respectively. Rg is the gate resistor. R_1 is chosen to be 22 kΩ (15 V Vbs); this high value helps to minimize the increased Miller capacitance effect from diode D1, and makes sure that there is not significant current being drawn from the HO output. The diode D_1 has the same characteristics as the bootstrap diode.

When the HO output goes high MOSFET Q1 turns on. Point X will be pulled down to a voltage that equals the voltage across the FET (V_{DS}) plus the voltage across diode D1.

$V_X = V_{D1} + V_{DS}$

In the circuit DSS16-01A is used as diodes D1 and D2, which has a 0.64 V forvard voltage.

$V_{DS} = I_S*R_{DS}$

In the circuit IRF530 MOSFET is used which has 0.16 Ω internal on resistance. The circuit is designed for 10 A overcurrent. So V_{DS} becomes 1.6 V, and V_X is 2.24 V.

For an IR2125 the CS pin threshold is 250 mV, therefore R_2 and R_3 are chosen such that when $V_X = 2.24$ V, then $V_Y = 250$ mV.

$V_Y = V_X \cdot R3/ (R2+R3)$

R_2 is chosen as $R_2 = 8$ kΩ

$R_3 = 1$ kΩ

CHAPTER 6

CONVERTER EXAMPLE

6.1 Boost Converter Design Example

The following example is given as a user guide for “Converter Design” GUI. The designed converter is simulated and real measurements are taken and compared in the following section

Step-1: On the MATLAB workspace, “converter_design” is written to start the application.

Step-2: “Boost” converter is selected on “Converter Design” section and “OK” button is pressed.

Step-3: The following design inputs are entered:

- V_{in} = 30 V
- V_o = 50 V
- R = 50 Ω
- f_s = 20000 Hz
- C = 100 μF
- L = 220 μH

Step-4: “Design” button is pressed. The following design outputs are obtained:

- Output Power = 50 W

- Duty Cycle = 40 %
- Minimum Load for DCM = 61.11 Ω
- Output Voltage Ripple = 0.2 V
- Inductor Current Ripple = 2.72 A

Step-5: "Continuity Check" button is pressed and it is seen that the designed converter operates in CCM (continuous conduction mode).

Step-6: "Auto Settings" button is pressed to set the simulation parameters.

Step-7: "Open Loop Simulation" button is pressed to simulate the designed converter.At the same time, real measurements are also taken by using an oscilloscope. The following voltage and current waveforms are obtained:

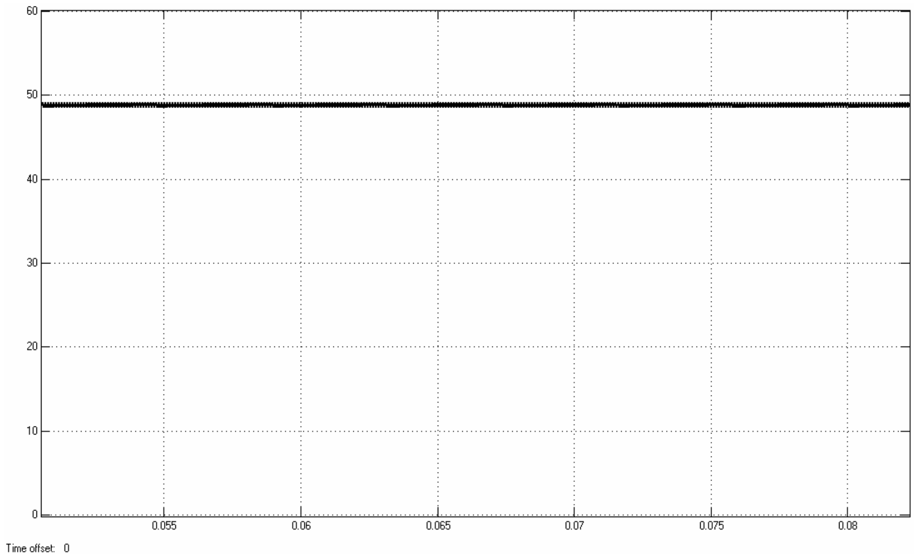

Figure 28 Simulation result of boost converter output voltage.

The average output voltage of the boost converter is measured as 48.8 V.

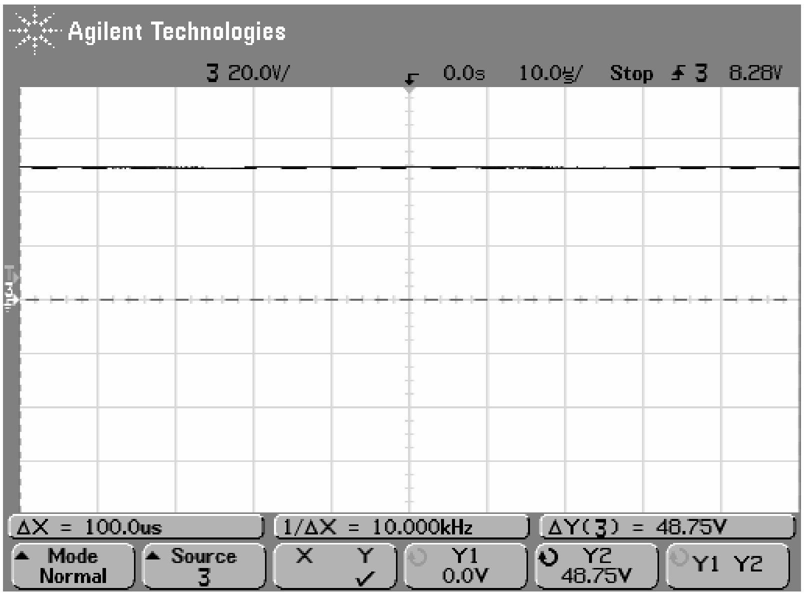

Figure 29 Boost converter output voltage (Oscilloscope result).

The output voltage is found 48.75 V. From the steady-state formula the output voltage is expected as 50 V, but because of the non-ideal components (internal inductor resistance, voltage drop on the diode and voltage drop on the MOSFET) the output voltage is measured as 48.75 V.

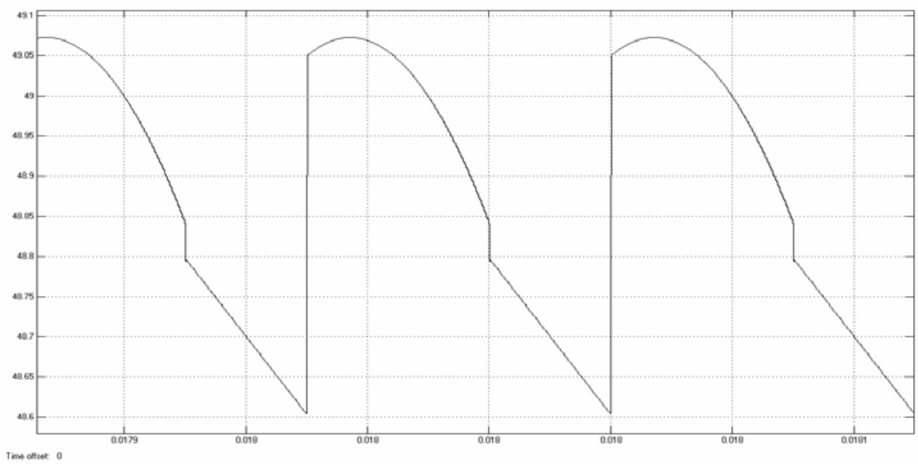

Figure 30 Zoom view of the output voltage and current (Simulation result, 20 µs/div time scale) .

From simulation the output voltage ripple is obtained as 472 mV.

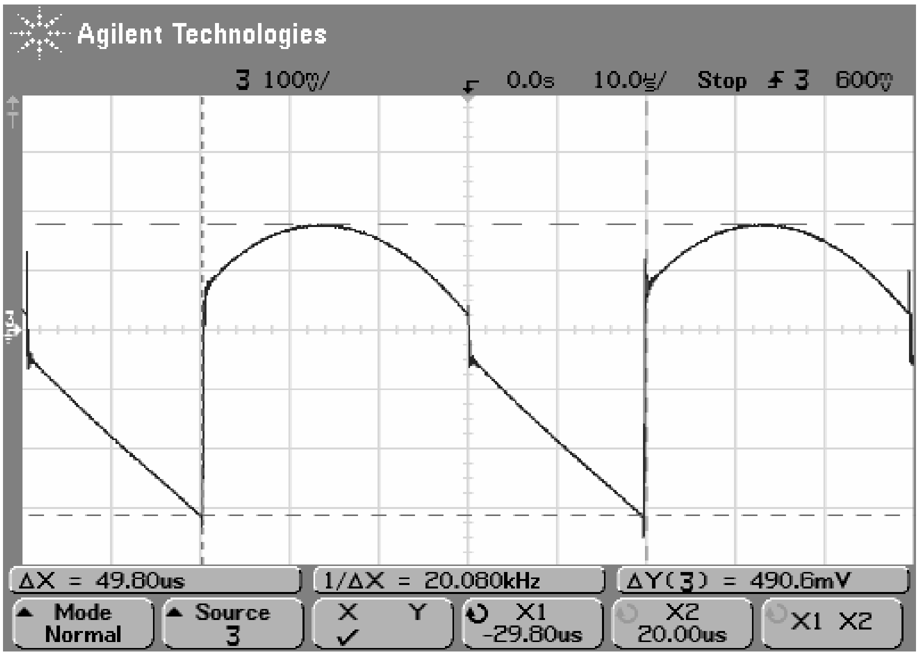

Figure 31 Output voltage in the AC mode of the oscilloscope.

The output voltage ripple is measured as 490.6 mV. It is seen that the simulation result and the real measurement are very close. The difference between the results found from steady-state formula and the real measurement result is because of the capacitor ESR effect. In the steady state formula the effect of the ESR is ignored. The ESR of the output capacitor of the boost converter is measured as 0.15 Ω, this value is added in the simulation.

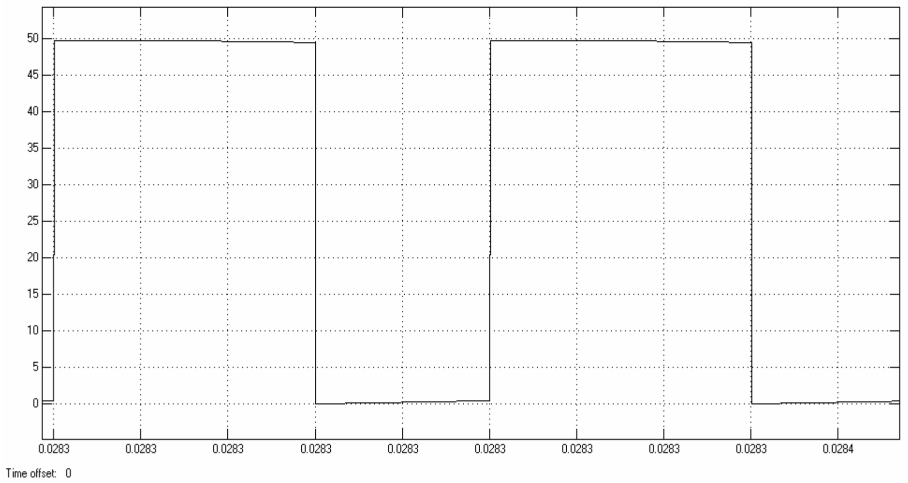

Figure 32 MOSFET voltage, V_{ds} (simulation result, 10 μs/div time scale).

From simulation the MOSFET V_{ds} voltage is obtained as 50 V when the MOSFET is off, and 0.05 V when it is on.

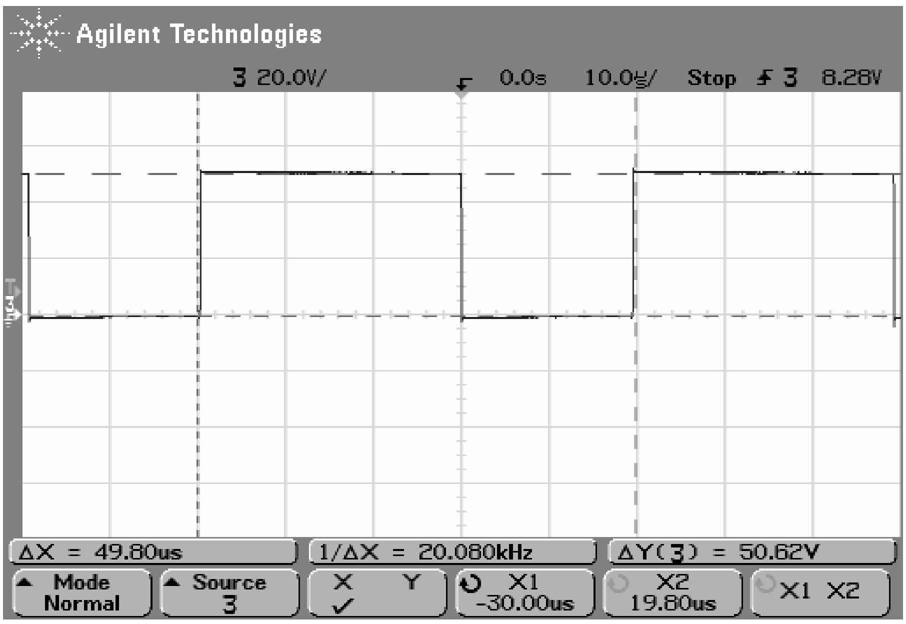

Figure 33 MOSFET voltage, V_{ds} (Oscilloscope result).

From the oscilloscope measure the MOSFET voltage is measured as 630 mV when it is on and 49.9 V when it is off. The voltage drop on MOSFET when it is off is equal to $V_{ds} = V_o$ – voltage drop on the diode. And when it is on is equal to $V_{ds} = R_{on} * I_{ind}$. In the boost converter IRF 530 MOSFET is used which has the following values [10]:

$R_{on} = 0.16\ \Omega$ and $L_{on} = 12$ nH.

These values are entered in the simulation model of the MOSFET.

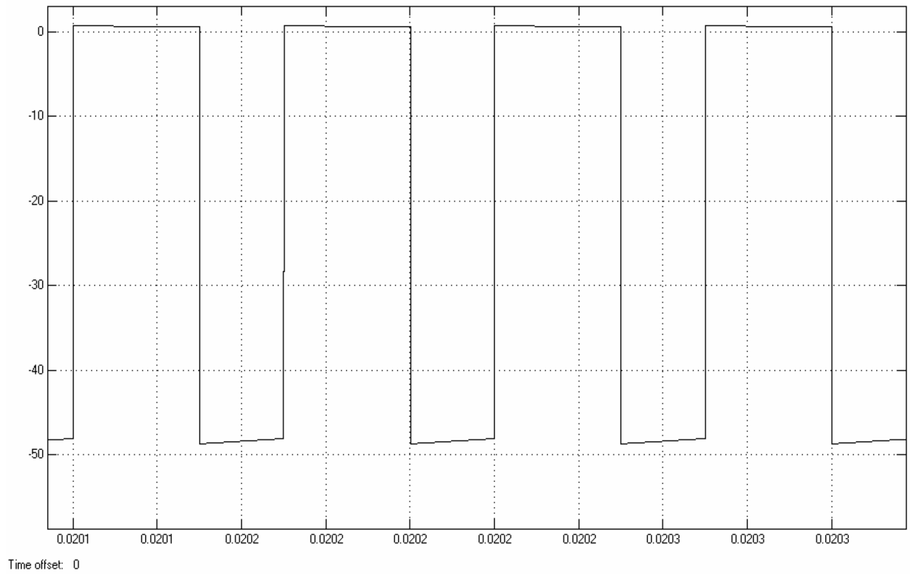

Figure 34 Diode voltage (simulation result, 20 μs/div time scale).

From simulation result diode voltage is obtained as 0.7 V when the diode is on and 48 V when it is off.

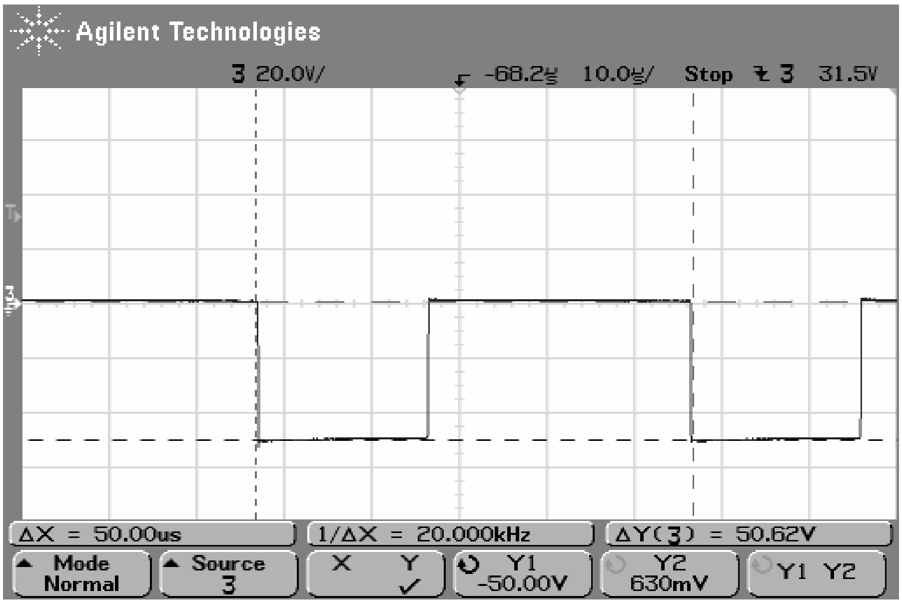

Figure 35 Diode voltage (Oscilloscope result).

From the oscilloscope the diode voltage is measured as 630 mV when it is on and 50 V when it is off. From simulation and measurement result it is seen that when diode is on voltage drop is 630 mV this is because in the boost converter DSS16-01A diode is used which has the value V_F = 0.64 V [11].

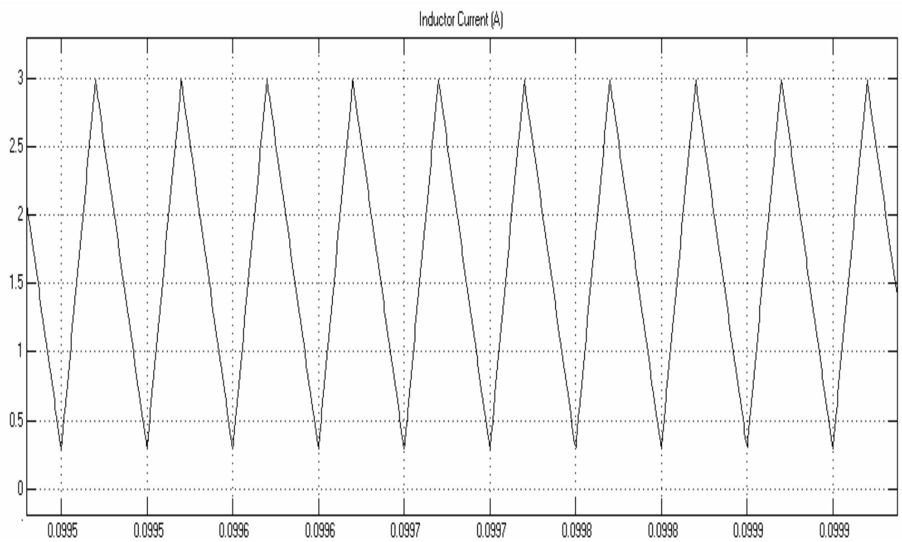

Figure 36 Inductor current (simulation result, 50 µs/div time scale).

Inductor current ripple is obtained as 2.65A peak-to-peak in the simulation.

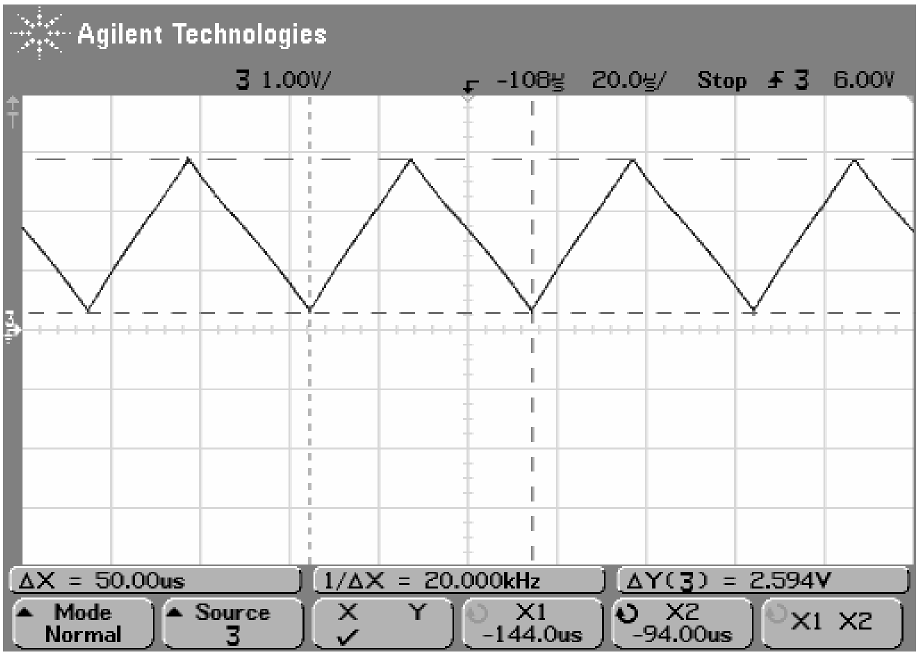

Figure 37 Inductor current (Oscilloscope result).

From the oscilloscope the inductor current ripple is measured as 2.594 A. It is seen that the simulation result and the real measurement are very close. The difference between the results found from steady-state formula and the real measurement result is because the inductor has the internal resistance. In the steady state formula this resistance is ignored. The internal resistance of the inductor of the boost converter is measured as 0.05 Ω, this value is added in the simulation.

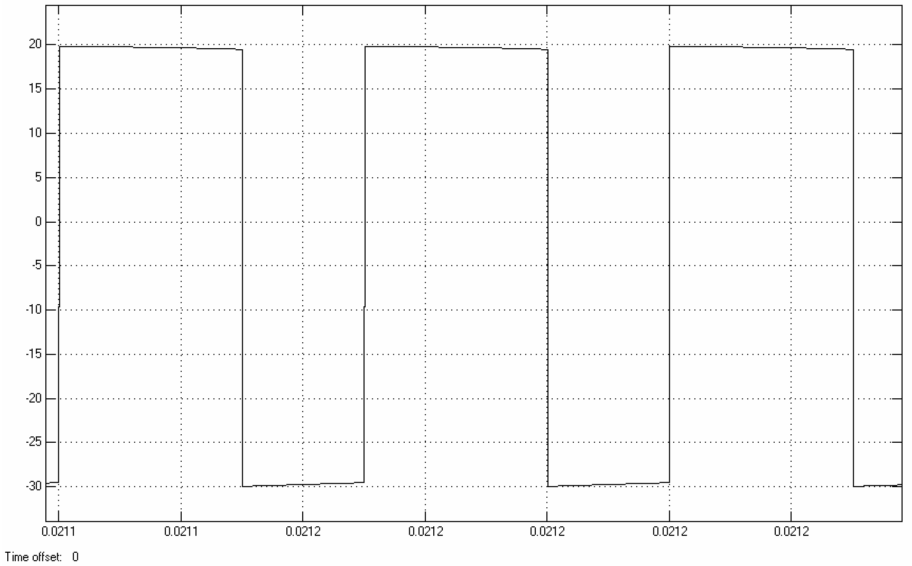

Figure 38 Inductor voltage (simulation result, 20 µs/div time scale).

From simulation result inductor voltage is obtained as 19.95 V when MOSFET is off and -29.93 V when MOSFET is on.

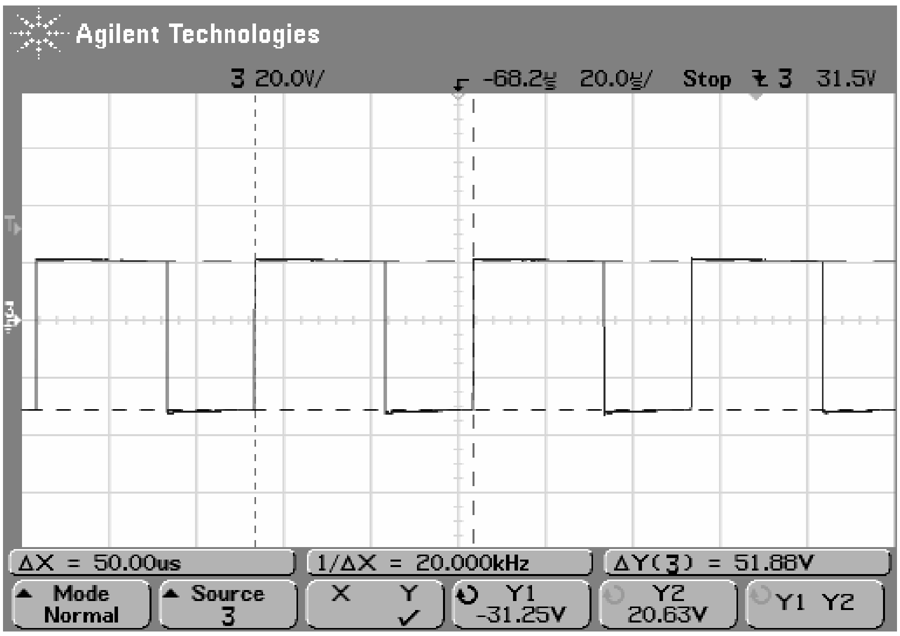

Figure 39 Inductor voltage (Oscilloscope result).

From the oscilloscope the inductor voltage is measured as 20.63 V when MOSFET is off and -31.25V when it is on.

Step-8: To observe the waveforms of the Boost converter in the discontinuous conduction mode the following design inputs are entered:

- V_{in} = 30 V
- V_o = 58.15 V
- R = 100 Ω
- f_s = 20000 Hz
- C = 100 μF
- L = 220 μH

Step-9: “Design” button is pressed. The following design outputs are obtained:

- Output Power = 33.81 W
- Duty Cycle = 40 %
- Minimum Load for DCM = 68.28 Ω
- Output Voltage Ripple = 0.11 V
- Inductor Current Ripple = 2.72 A

Step-10: “Continuity Check” button is pressed and it is seen that the designed converter operates in DCM (discontinuous conduction mode).

Step-11: “Auto Settings” button is pressed to set the simulation parameters.

Step-12: “Open Loop Simulation” button is pressed to simulate the designed converter.

At the same time, real measurements are also taken by using an oscilloscope.

The following voltage and current waveforms are obtained:

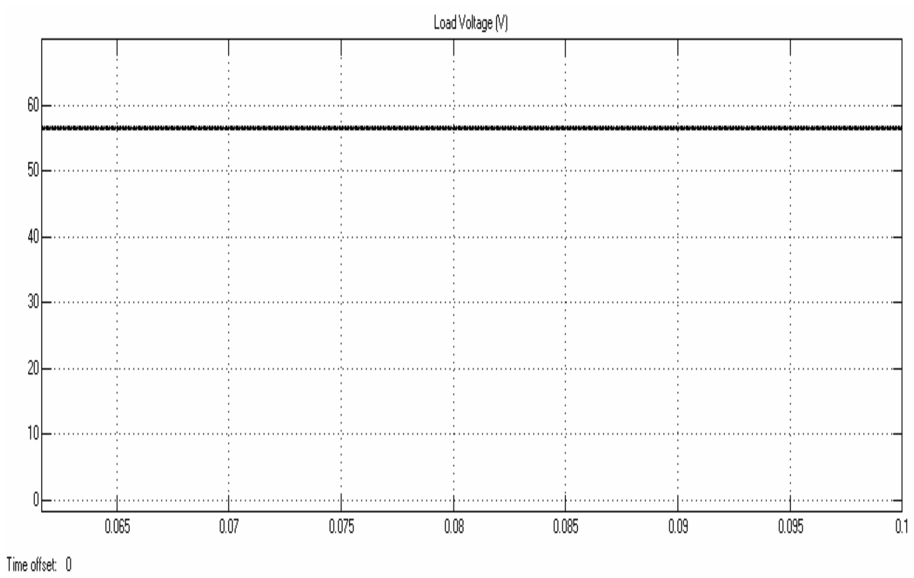

Figure 40 Output voltage (Simuation result, 5 ms/div time range).

The average output voltage of the boost converter is obtained as 56.5 V.

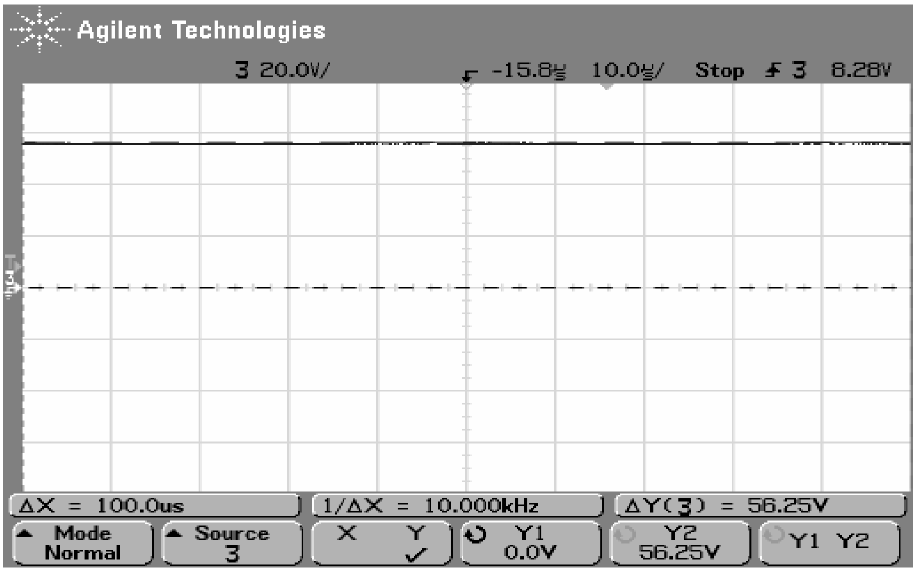

Figure 41 Output voltage (oscilloscope is at DC mode).

From the oscilloscope the output voltage is measured as 56.25 V. From the steady-state formula the output voltage is expected as 58.15 V, but because of the non-ideal components (internal inductor resistance, voltage drop on the diode and voltage drop on the MOSFET) the output voltage is measured as 56.25 V.

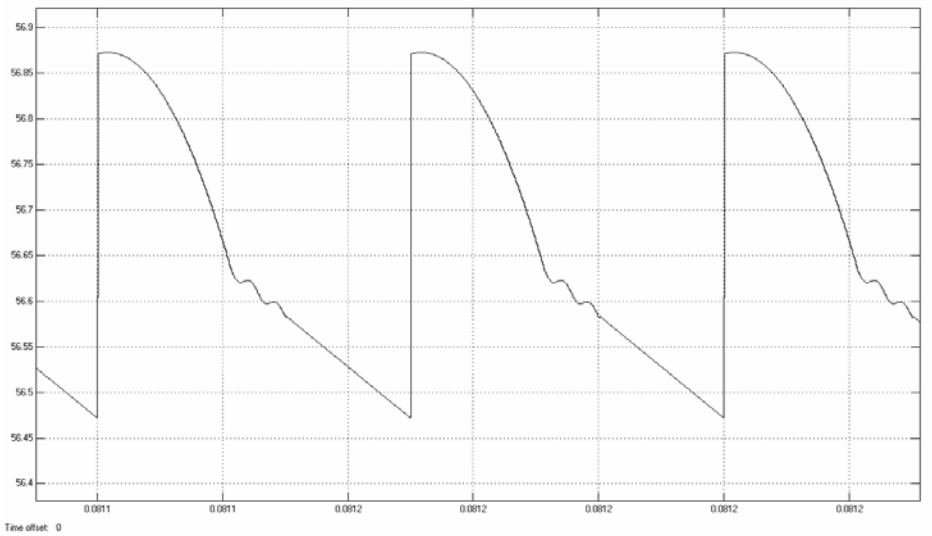

Figure 42 Zoom view of the output voltage and current (Simulation result, 20 μs/div time range).

From simulation the output voltage ripple is obtained as 415 mV.

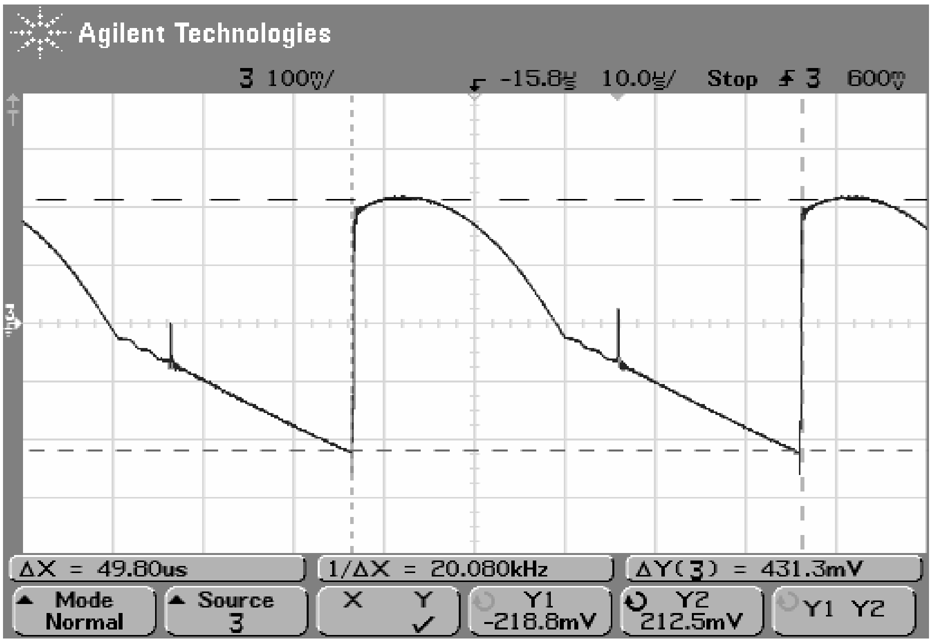

Figure 43 Output voltage in the AC mode of the oscilloscope.

The output voltage ripple is measured as 431.3 mV, which is very close to the simulation result. The difference between the results found from steady-state formula and the real measurement result is again because of the capacitor ESR effect. In the steady state formula the effect of the ESR is ignored.

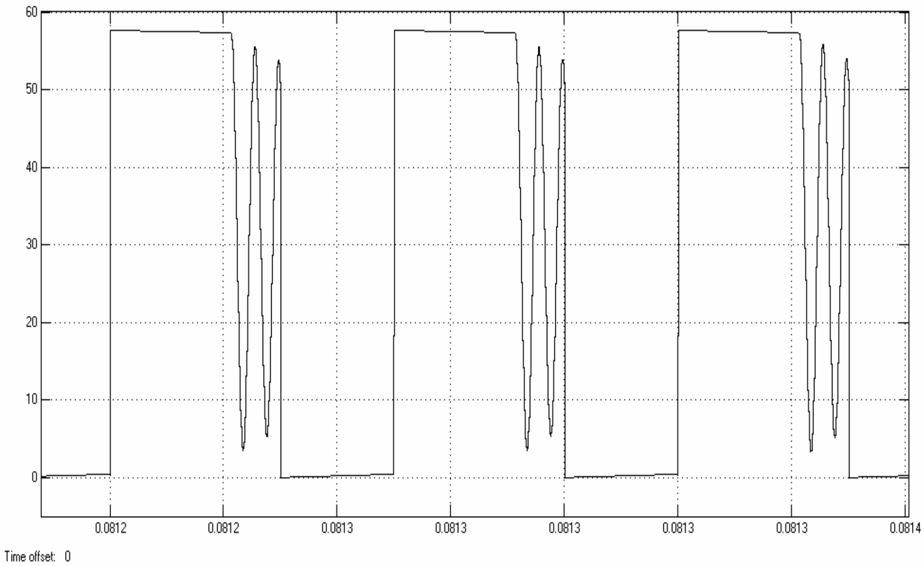

Figure 44 MOSFET voltage, V_{ds} (simulation result, 20 µs/div time range).

From simulation the MOSFET voltage V_{ds} is obtained as 58 V when MOSFET is off, and 0.05 V when it is on.

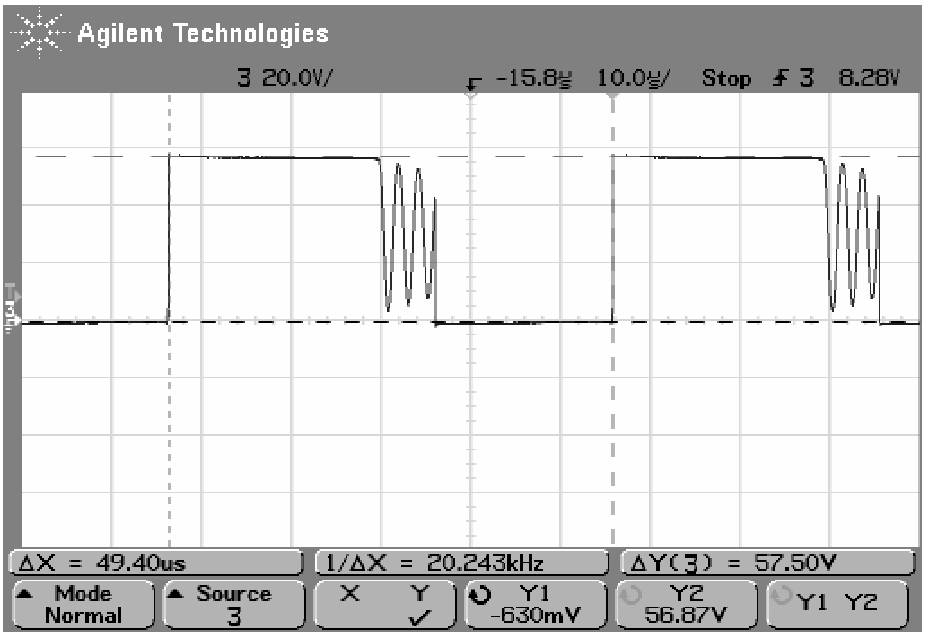

Figure 45 MOSFET voltage, V_{ds} (Oscilloscope result).

From the oscilloscope the MOSFET voltage is measured as 630 mV when it is on and 56.87 V when it is off.

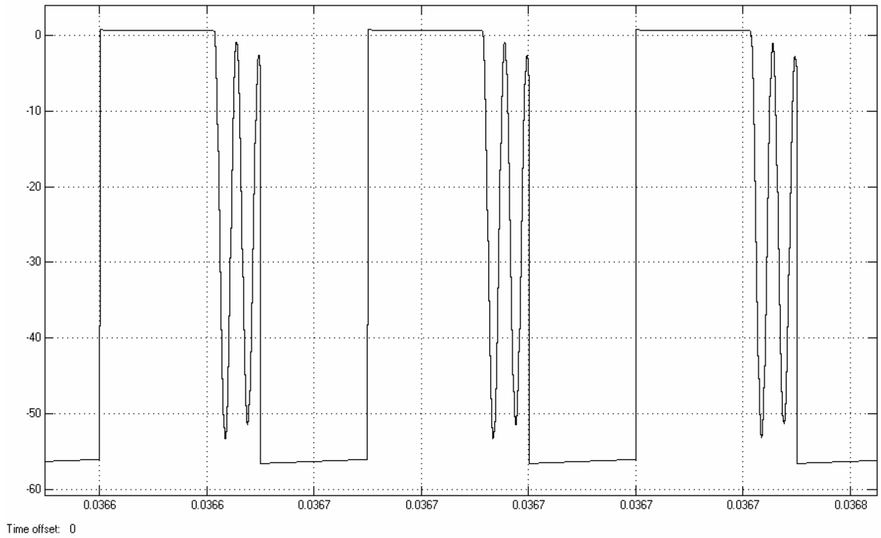

Figure 46 Diode voltage (simulation result, 20 μs/div time range).

From simulation result diode voltage is measured as 0.8 V when the diode is on and 56 V when it is off.

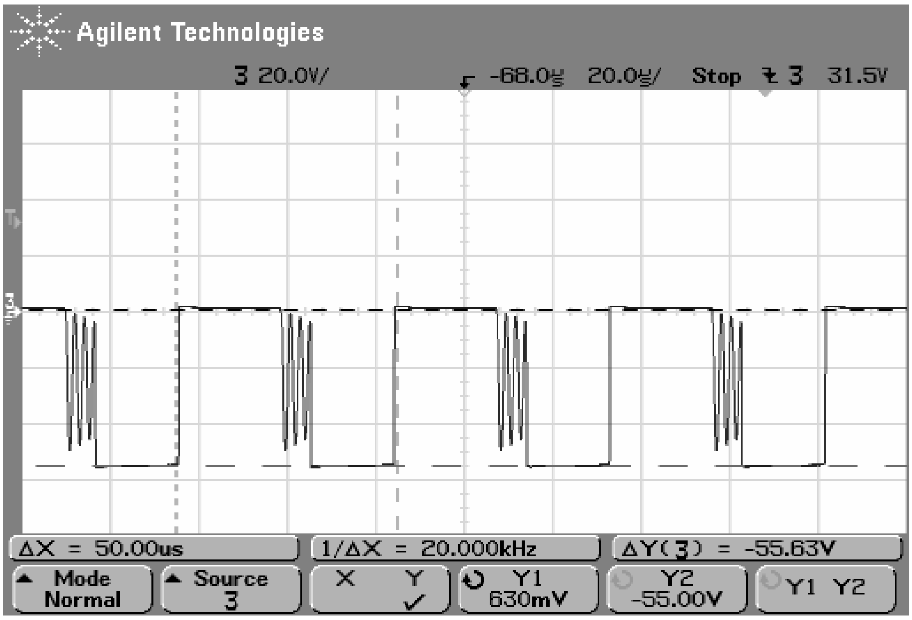

Figure 47 Diode voltage (Oscilloscope result).

From the oscilloscope the MOSFET voltage is measured as 630 mV when it is on and 55 V when it is off.

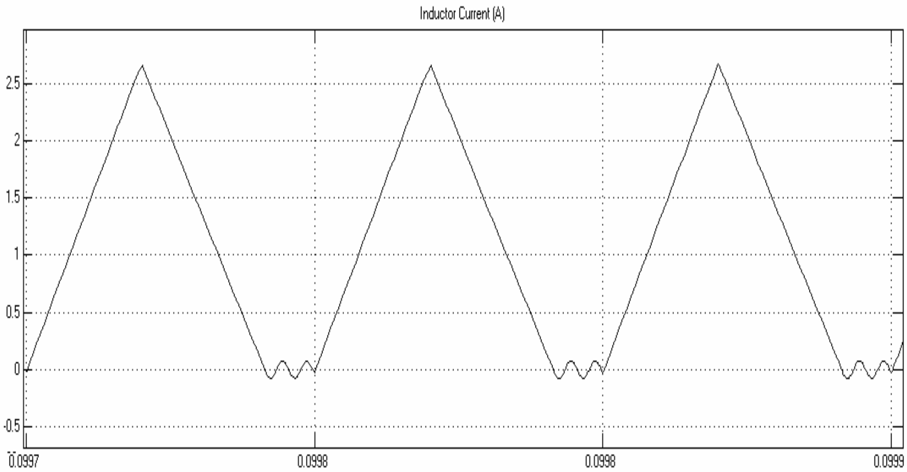

Figure 48 Inductor current (simulation result, 50 µs/div time range).

Inductor current ripple is obtained as 2.63 A peak-to-peak in the simulation.

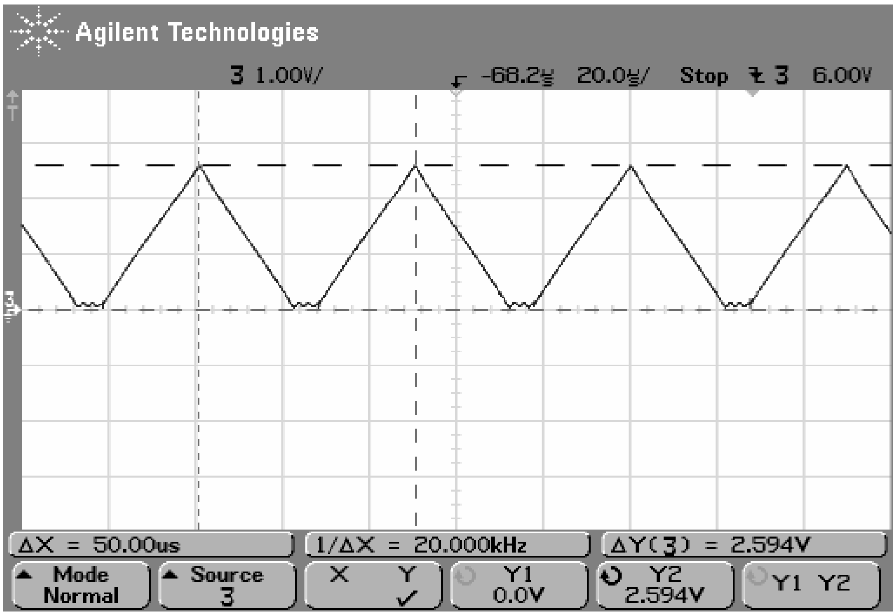

Figure 49 Inductor current (Oscilloscope result).

From the oscilloscope the inductor current ripple is measured as 2.594 A. From both simulation result and oscilloscope measurement it is seen that the inductor current is reached to the zero, so it can be said that the boost converter is operated in discontinuous conduction mode. Again the difference between the results found from steady-state formula and the real measurement result is because of the inductor internal resistance.

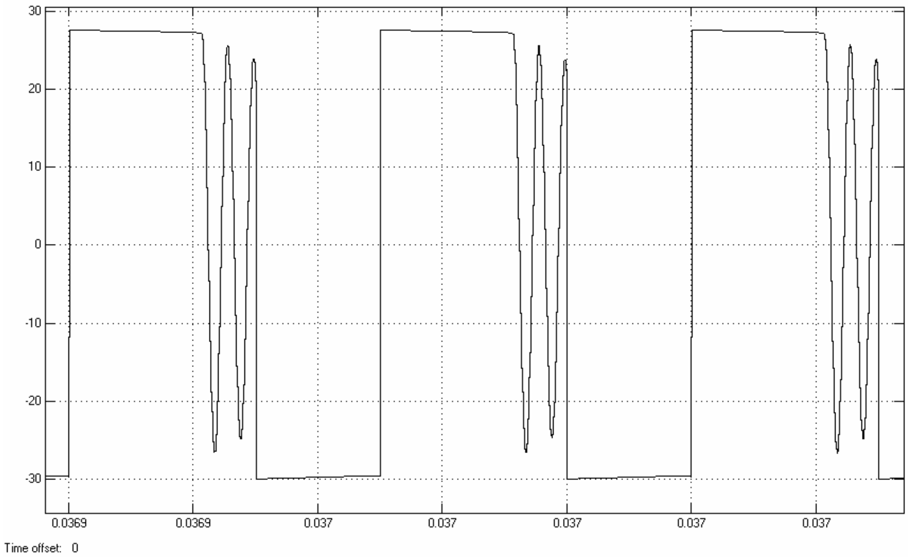

Figure 50 Inductor voltage (simulation result, 20 µs/div time range).

From simulation result inductor voltage is measured as 27.35 V when MOSFET is off and -29.93 V when MOSFET is on.

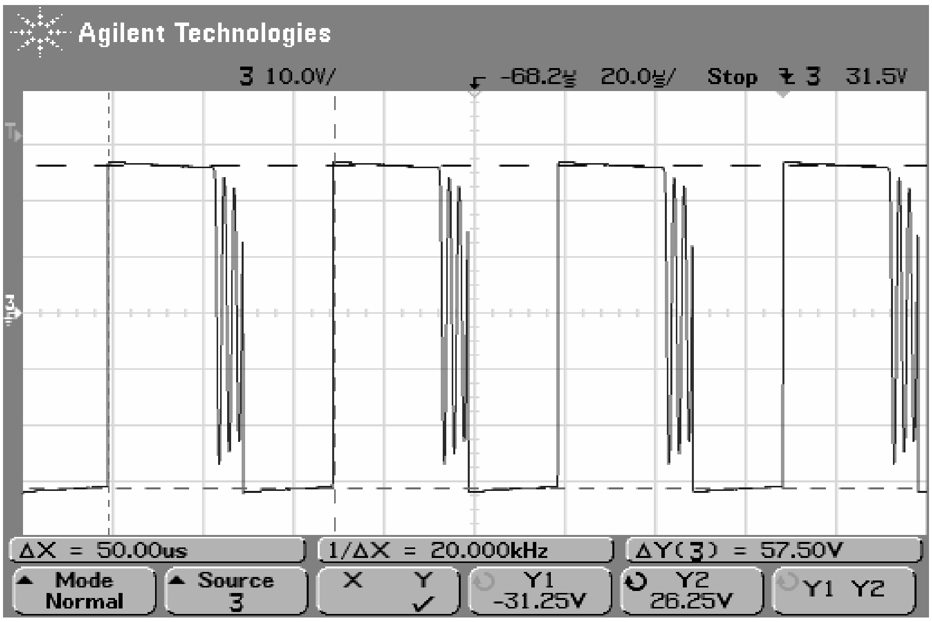

Figure 51 Inductor voltage (Oscilloscope result).

From the oscilloscope the inductor voltage is measured as 26.25 V when MOSFET is off, and -31.25 V when it is on.

In the DCM as seen from the results there is low frequency parasitic oscillation on the switch voltage and the input current. This is because at the moment the inductor current becomes zero, the switch voltage should adopt the input votage, and the input current should remain zero. Nevertheless, for real switches, a network, consisting of parasitic capacitances C_{OSS} of the the switch and C_D of the diode, and the inductor L (Figure 52) starts the oscillating at that instant [12].

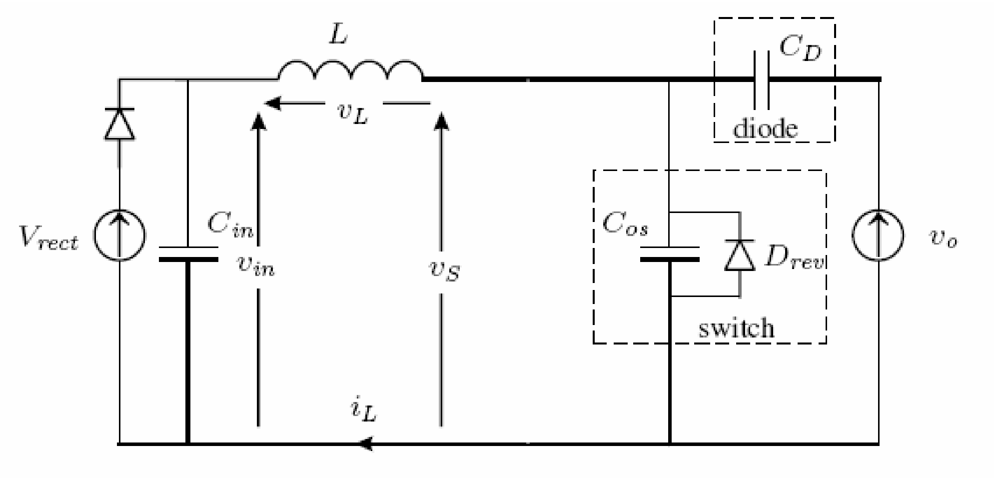

Figure 52 Parasitic network causing oscillations [12].

The switch voltage oscillation is described approximately as [12]:

$$V_S(t) = V_{in} + (V_O - V_{in})\cos(w_n(t - t_2))$$

Where:

$$w_n = \frac{1}{\sqrt{LC_n}}$$

The capacitance C_n, in these expressions is equal to the parallel connection of the switch capacitance and the diode capacitance [12].The followings are boost converter switch and diode parasitics taken from their datasheets;

- C_{oss} of MOSFET (IRF530) is equal to 210 pF
- C_D of diode (DSS16-01A) is equal 140 pF

By using these parasitic capacitance values, the following parasitic oscillation frequency is calculated:

$Wn = 3.17 * 10^6$ rad/s

From simulation and measurement results, the following parasitic oscillation frequency is obtained:

$Wn = 3.14 * 10^6$ rad/s

So, simulation and real measurement verify each other.

Step-13: To observe the waveforms of the boost converter at 50 kHz the following design inputs are entered:

- $V_{in} = 30$ V
- $V_o = 50$ V
- R = 100 Ω
- $f_s = 50000$ Hz
- C = 100 µF
- L = 220 µH

Step-14: "Design" button is pressed. The following design outputs are obtained:

- Output Power = 25 W
- Duty Cycle = 40 %

- Minimum Load for DCM = 152.77 Ω
- Output Voltage Ripple = 0.04 V
- Inductor Current Ripple = 1.09 A

Step-15: “Continuity Check” button is pressed and it is seen that the designed converter operates in CCM.

Step-16: “Auto Settings” button is pressed to set the simulation parameters.

Step-17: “Open Loop Simulation” button is pressed to simulate the designed converter.

At the same time, real measurements are also taken by using an oscilloscope.

The following voltage and current waveforms are obtained:

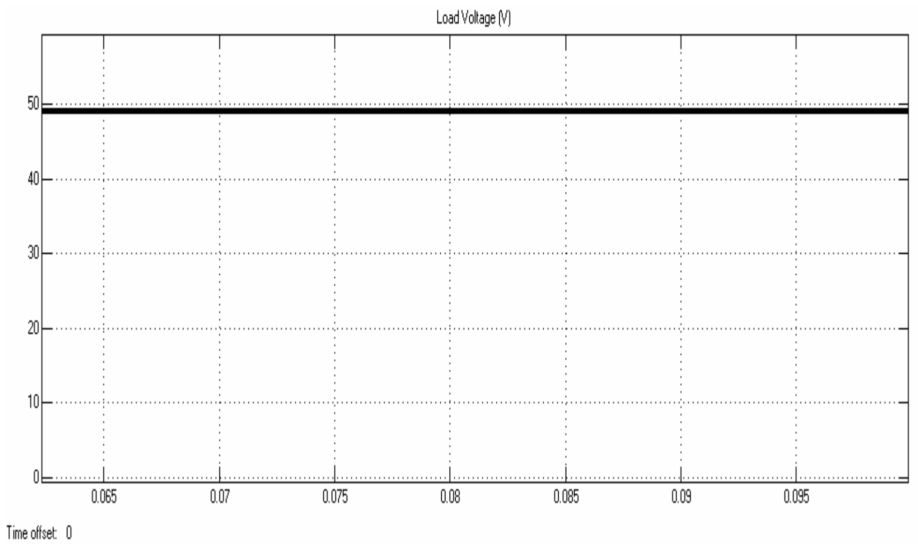

Figure 53 Output voltage (Simuation result, 5 ms/div time range).

The average output voltage of the boost converter is obtained as 49.275 V.

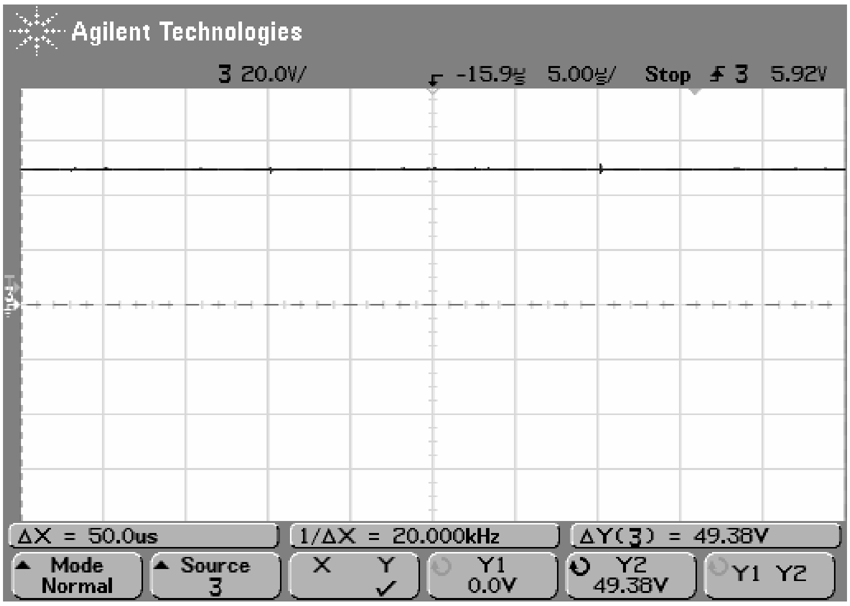

Figure 54 Output voltage (oscilloscope is at DC mode).

From the oscilloscope the output voltage is measured as 49.38 V. From the steady-state formula the output voltage is expected as 50 V, but again because of the non-ideal components the output voltage is measured as 56.25 V.

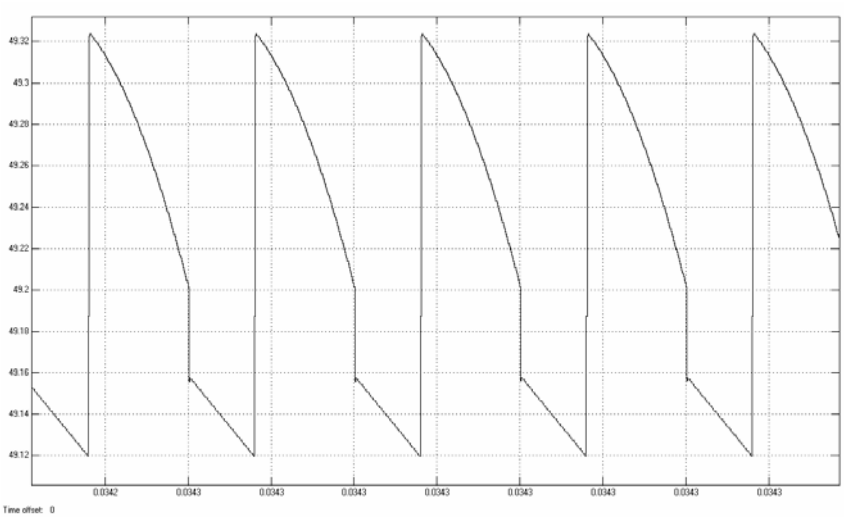

Figure 55 Zoom view of the output voltage and current (Simulation result, 10 μs/div time range).

From simulation the output voltage ripple is obtained as 202 mV.

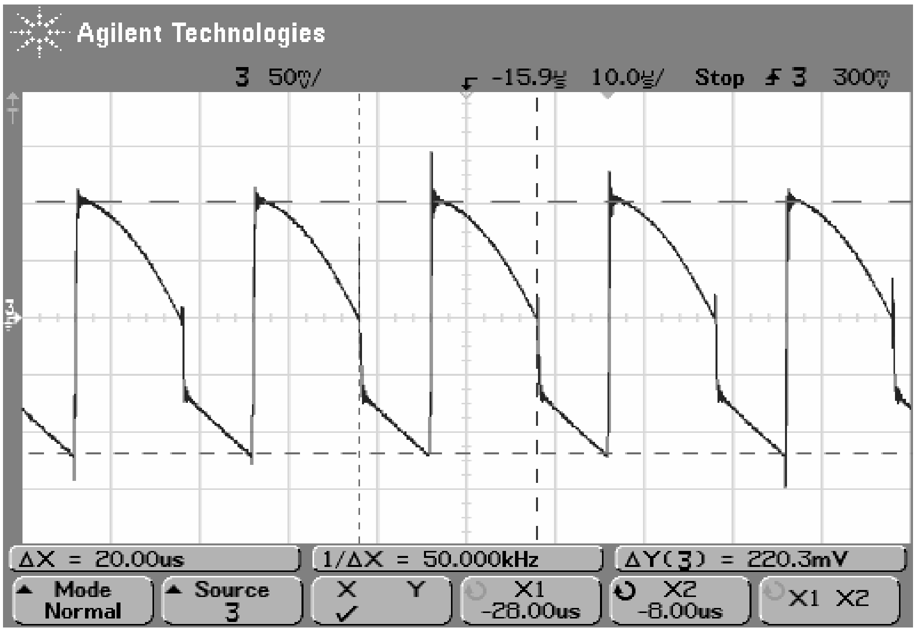

Figure 56 Output voltage in the AC mode of the oscilloscope.

The output voltage ripple is measured as 220.3 mV, which is very close to the simulation result. It is seen that with increasing the switching frequency the output voltage ripple is decreased. Again the difference between the result found from steady-state formula and the real measurement result is because of the capacitor ESR effect.

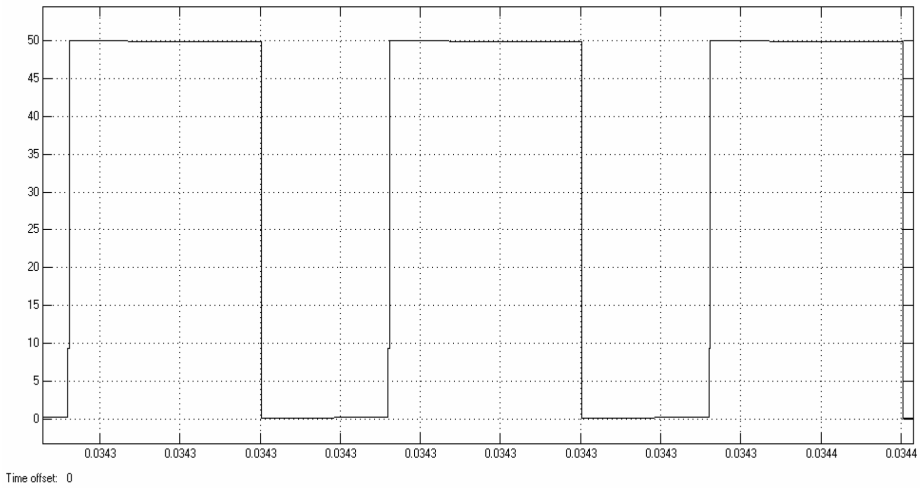

Figure 57 MOSFET voltage, V_{ds} (simulation result, 5 µs/div time range).

From simulation the MOSFET voltage V_{ds} is obtained as 50 V when MOSFET is off, and 0.05 V when it is on.

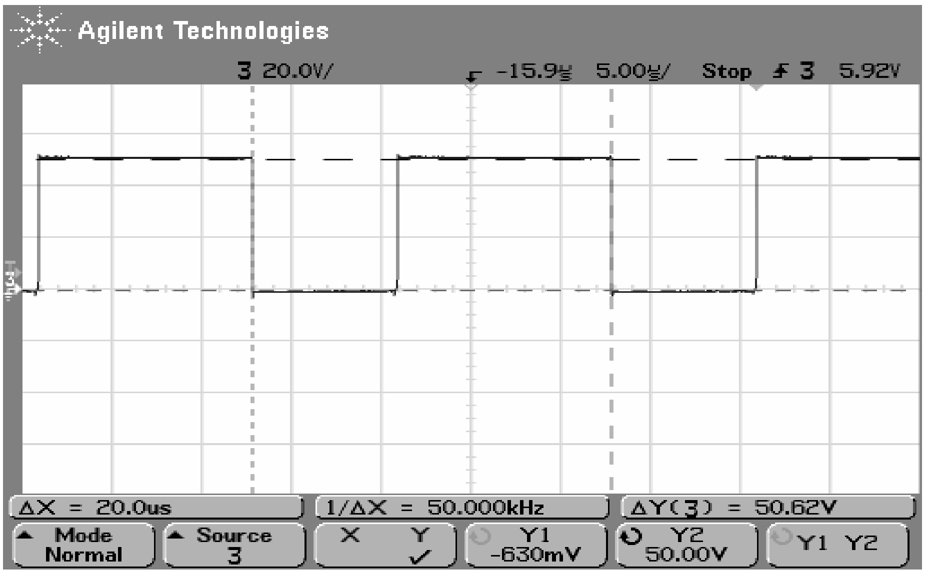

Figure 58. MOSFET voltage, V_{ds} (Oscilloscope result).

From the oscilloscope the MOSFET voltage is measured as 630 mV when it is on, and 50 V when it is off.

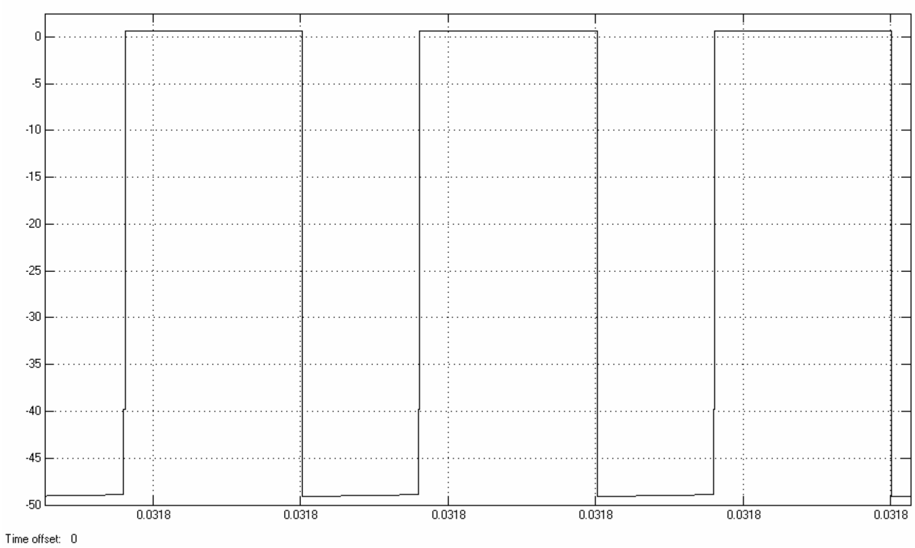

Figure 59 Diode voltage (simulation result, 10 μs/div time range).

From simulation result the diode voltage is measured as 0.8 V when the diode is on and 49.2 V when it is off.

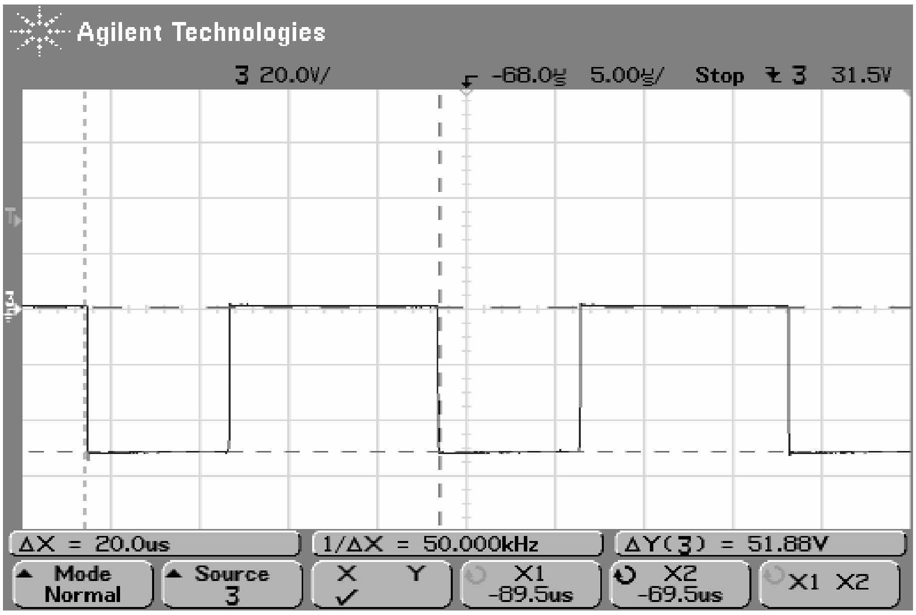

Figure 60 Diode voltage (Oscilloscope result).

From the oscilloscope the MOSFET voltage is measured as 630 mV when it is on and 51.25 V when it is off.

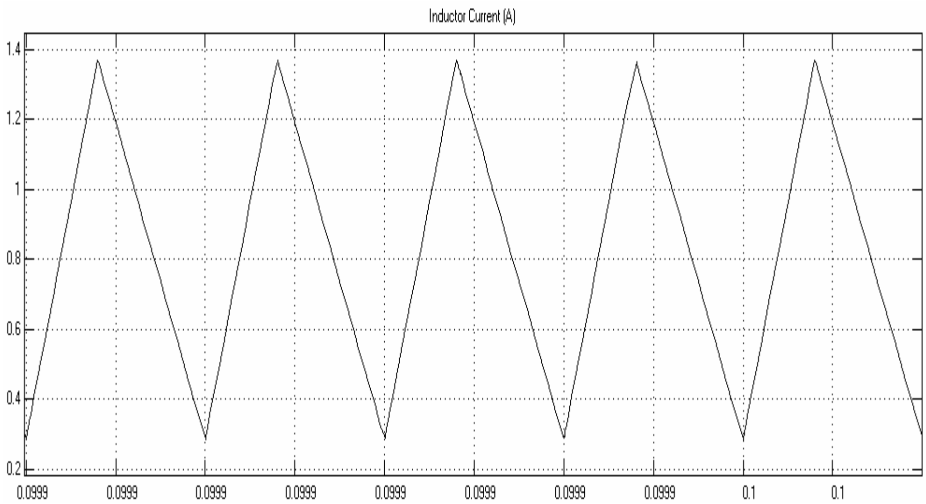

Figure 61 Inductor current (simulation result, 10 µs/div time range).

Inductor current ripple is obtained as 1.15 A peak-to-peak in the simulation.

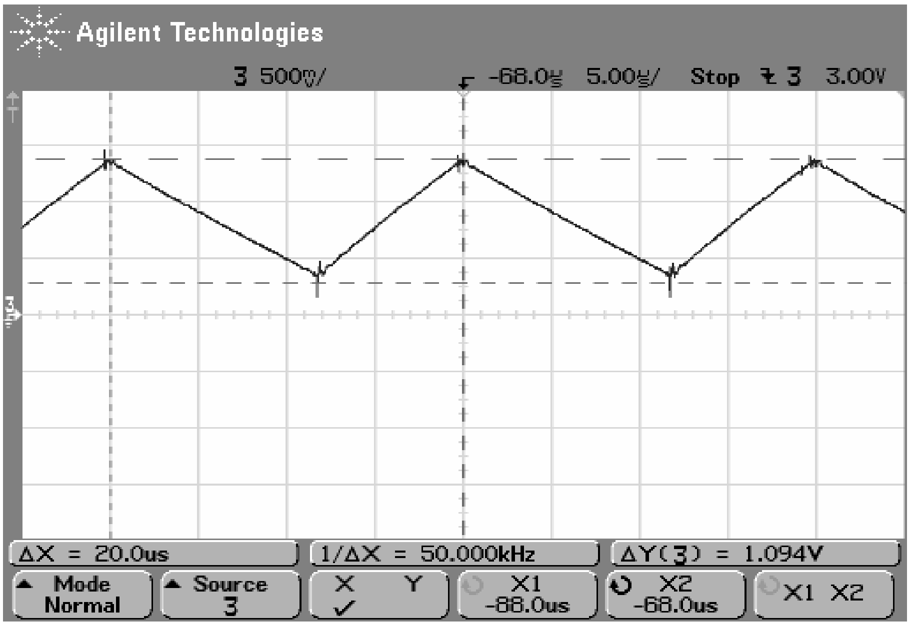

Figure 62 Inductor current (Oscilloscope result).

From the oscilloscope the inductor current ripple is measured as 1.094 A. It is seen that by increasing the switching frequency the inductor current ripple is reduced and converter is operated in continuous cnducton mode. Again the difference between the results found from steady-state formula and the real measurement result is because of the inductor internal resistance.

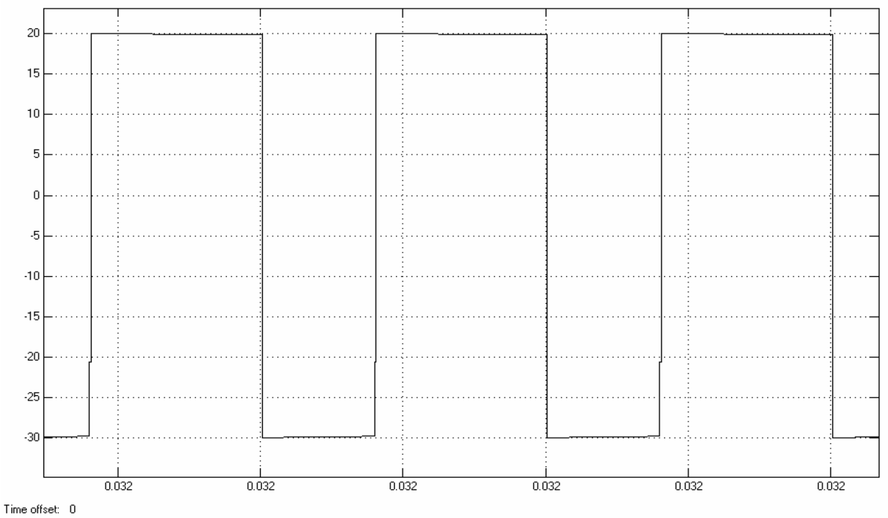

Figure 63 Inductor voltage (simulation result, 10 μs/div time range).

From simulation result the inductor voltage is measured as 21.1 V when MOSFET is off and -29.93 V when it is on.

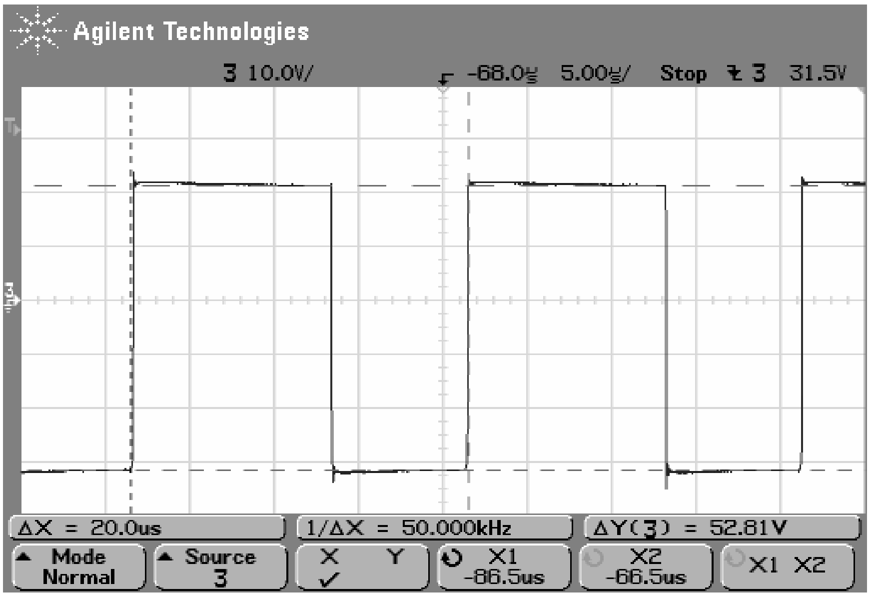

Figure 64 Inductor voltage (Oscilloscope result).

From the oscilloscope the inductor voltage is measured as 21.25 V when the MOSFET is off and -31.51 V when it is on.

Step-18: To observe the closed-loop characteristic of the boost converter, the following design inputs are entered in the "converter design" tool:

- V_{in} = 30 V
- V_o = 50 V
- R = 100 Ω
- f_s = 20000 Hz
- C = 100 μF
- L = 220 μH

Step-19: "Design" button is pressed. The following design outputs are obtained:

- Output Power = 25 W
- Duty Cycle = 31.2694 %
- Minimum Load for DCM = 61.111 Ω
- Output Voltage Ripple = 0.07817 V
- Inductor Current Ripple = 2.13201 A

Step-20: "Continuity Check" button is pressed and it is seen that the designed converter operates in DCM.

Step-21: "Frequency Response" button is pressed in the "Controller Design" part. The following figure is obtained.

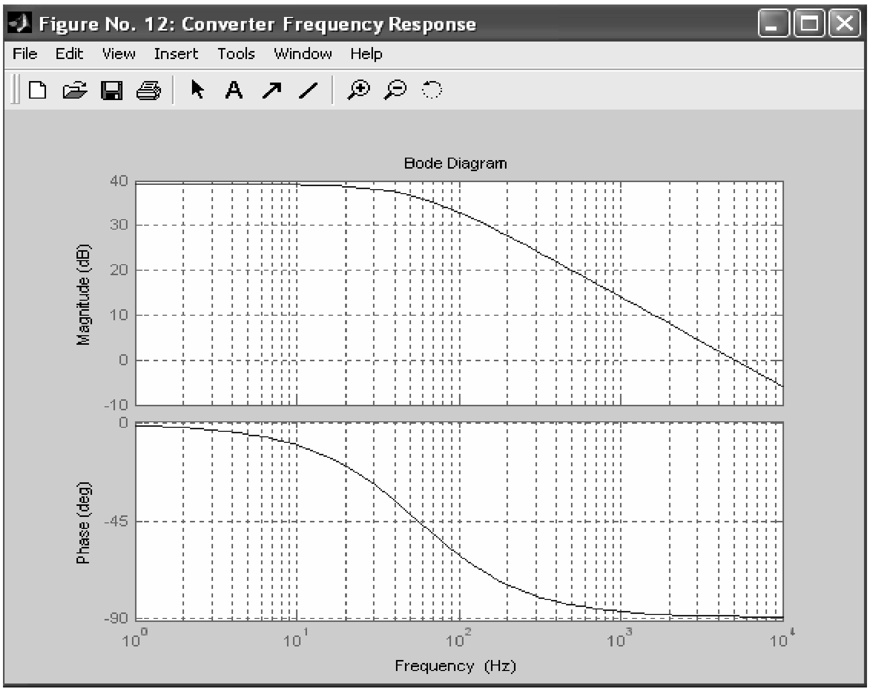

Figure 65 Bode plot of the open-loop boost converter.

Note: When the user realizes the design, another curve named "Design Summary" also plots the frequency responses obtained from converter transfer function "G_{vd}" to the compensated loop transfer function "T" on a same plot. This will help the user to view the entire frequency response summary from start to end of the design. During design, the user can also use this design summary plot at any time.

Step-22: "Poles/Zeroes" button is pressed in "Small-Signal Model (G_{vd})" section. The converter transfer function has one pole:

- $p_1 = -350$

"Small-Signal Model (G_{vd})" has no zero.

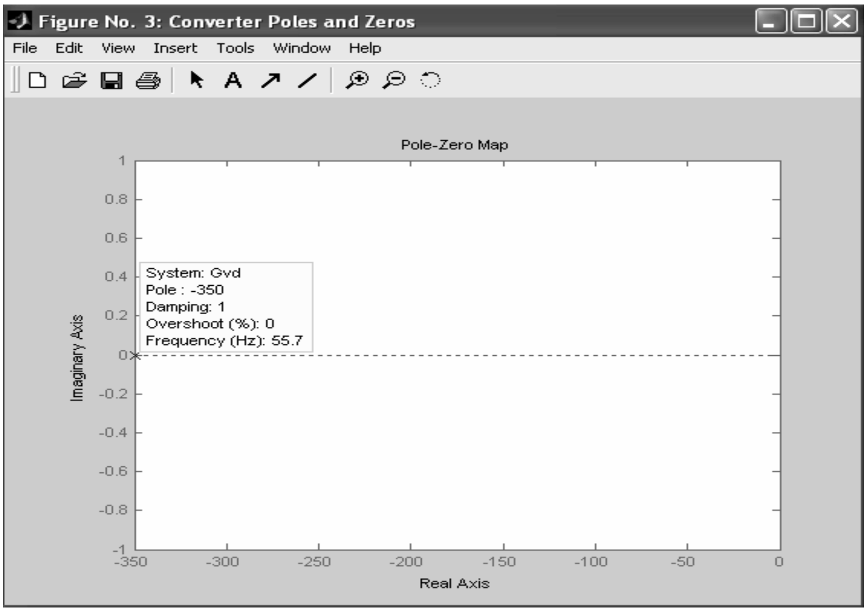

Figure 66 Poles and zeroes of "Small-Signal Model (G_{vd}).

Step-23: The amplitude of the sawtooth signal "V_m" and feedback gain "H" in the "Uncompensated Loop (T_u)" section is entered then "Set Model" button is pressed.

- $V_m = 5$
- H = 0.083

Step-24: "Frequency Response" button is pressed in "Uncompensated Loop (T_u)" section and the following are observed:

- Phase Margin = 131.24^o
- Cut-off Frequency = 399.15 rad/s (= 63.52 Hz)

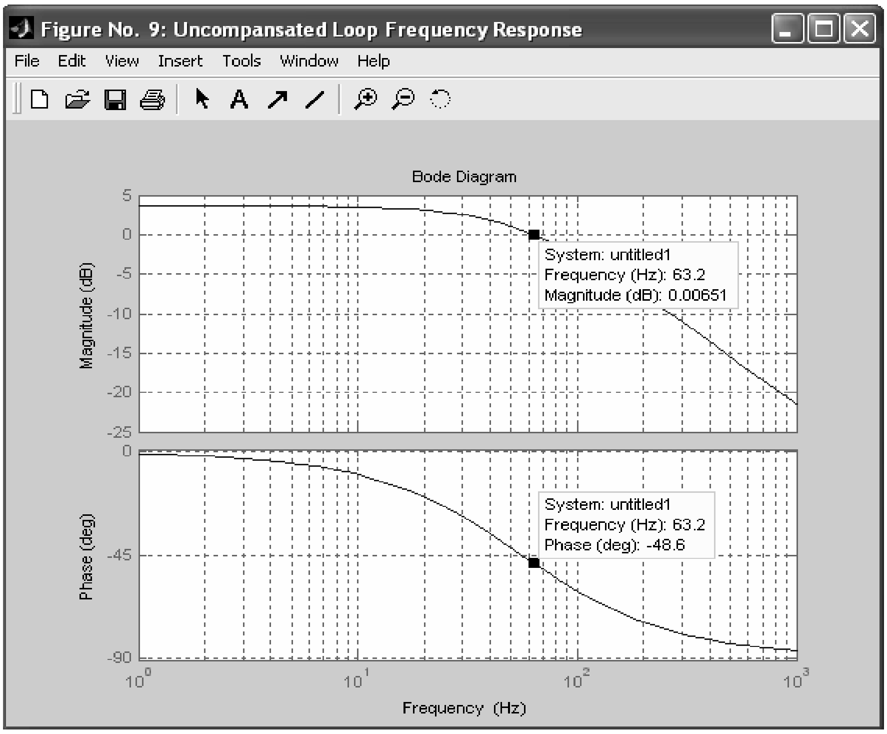

Figure 67 Frequency Response of "Uncompensated Loop (T_u)".

The uncompensated loop transfer function is:

```
>> Tu

Transfer function:
 530.9
-------
s + 350
```

Step-25: "Poles/Zeroes" button in "Uncompensated Loop (T_u)" section is pressed and the following figure is observed:

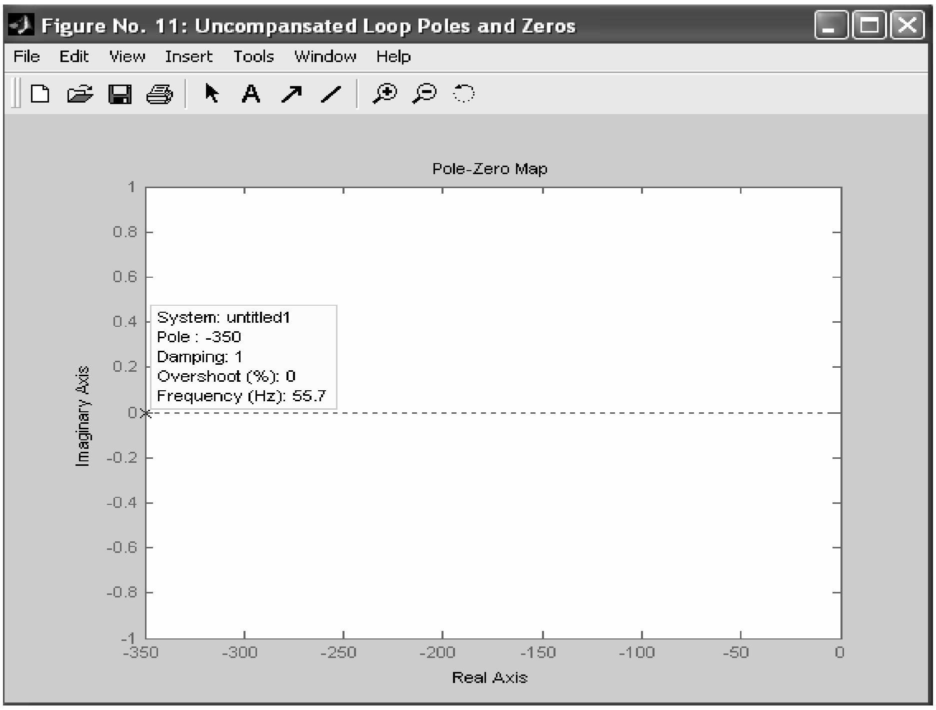

Figure 68 Poles and zeroes of "Uncompensated Loop (Tu)".

The uncompensated converter transfer function has one pole which is:

- p_1 = -350j

This is same for the converter transfer function "G_{vd}". This is the desired result, because "T_u" is equal to "G_{vd}" multiplied by "H/V_m".

Step-26: The controller PI constants are entered:

- $K_p = 7.35$
- $K_i = 890$

Step-27: When the"Frequency Response" button is preesed in "Compensated Loop (T)" window, the following figure is obtained (

Figure 69).

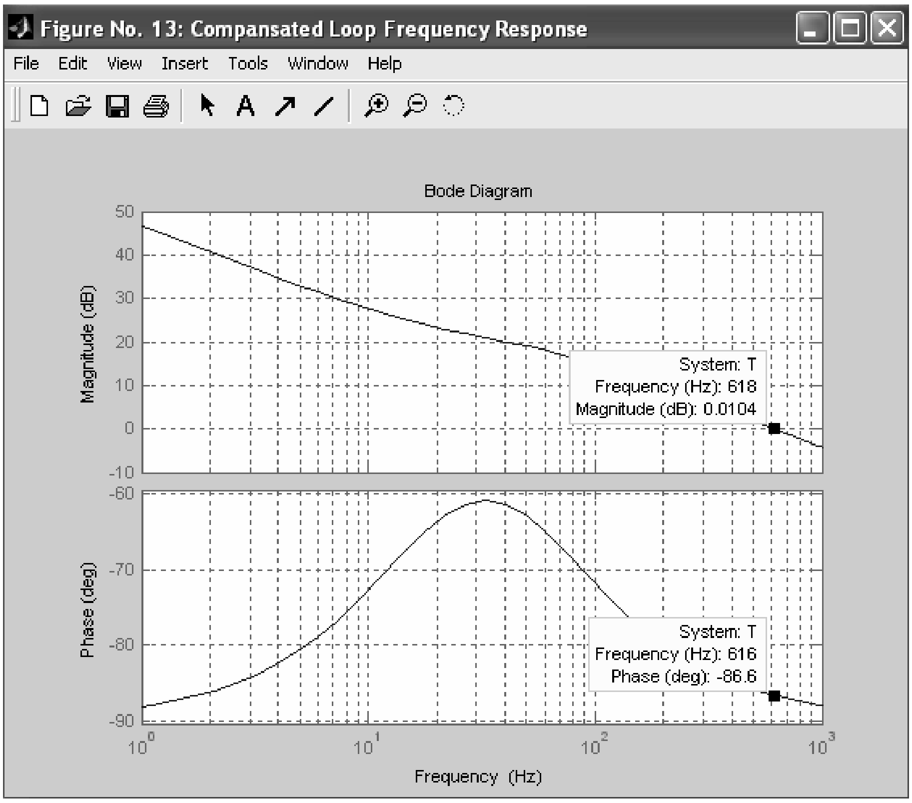

Figure 69 Frequency Response of "Compensated Loop (T)".

It is seen that the compensated loop transfer function has:

- Phase Margin = 93.4^{o}
- Cut-off Frequency = 619 Hz

After finishing the application, the user can see the compensated loop transfer function by typing "T" on MATLAB workspace as shown below:

```
>> T

Transfer function:
3902 s + 4.725e005
------------------
   s^2 + 350 s
```

Step-28: The“Poles/Zeroes” button in “Compensated Loop (T)” section is pressed and the following figure is seen (Figure 70):

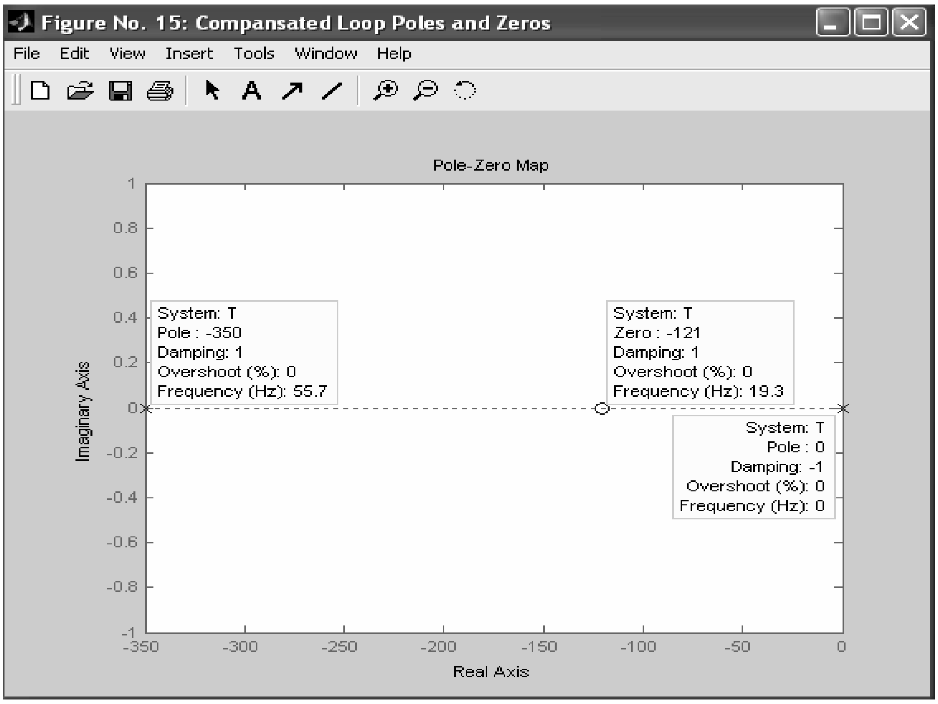

Figure 70 Poles and Zeroes of “Compensated Loop (T)”

It is seen that the compensated loop transfer function has two poles and one zero which are:

- p_1 = -350j
- p_2 = 0
- z_1 = -121

Step-29: “Auto Settings” button is pressed to set the simulation parameters.

Step-30: "Manual Settings" button is pressed to set the load regulation time and value. The following settings are entered on "Converter Design" GUI:

- R (Load): 100 Ω
- Reference Change: Final reference = 0, Change time = 1 sec.
- Load Regulation: Final Load = 200 Ω, Change time = 0.1 s
- Line Regulation: Amplitude = 0, Frequency = 0, Change time = 1 s

Step-31: "Closed Loop Simulation" button is pressed to start the simulation. The following output voltage waveform is obtained:

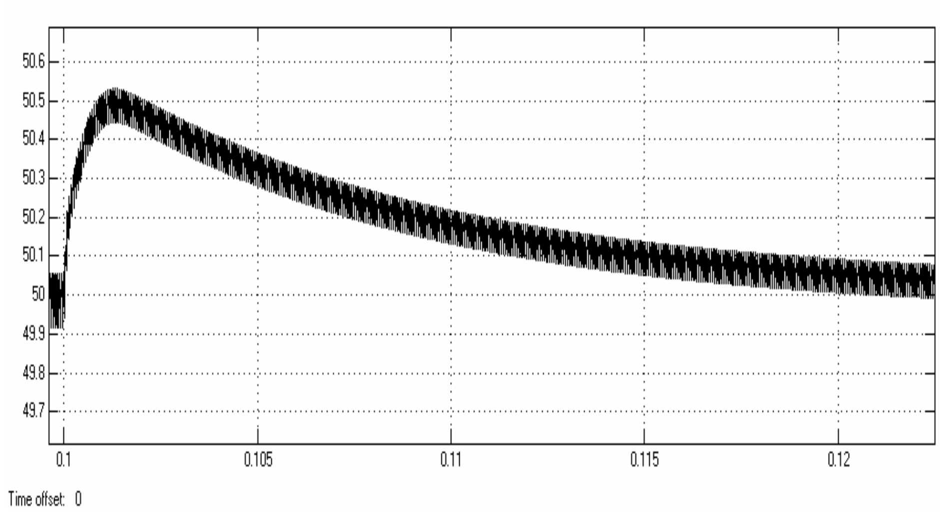

Figure 71 Simulation result of the boost converter load characteristics for a load change (at t = 0.1 s the load is changed from 100 Ω to 200 Ω).

In the simulation the load is changed from 100 Ω to 200 Ω. From simulation result the settling time where the output voltage decreases to 50 V is measured as 22 ms, and the maximum overshoot is measured as 0.5 V.

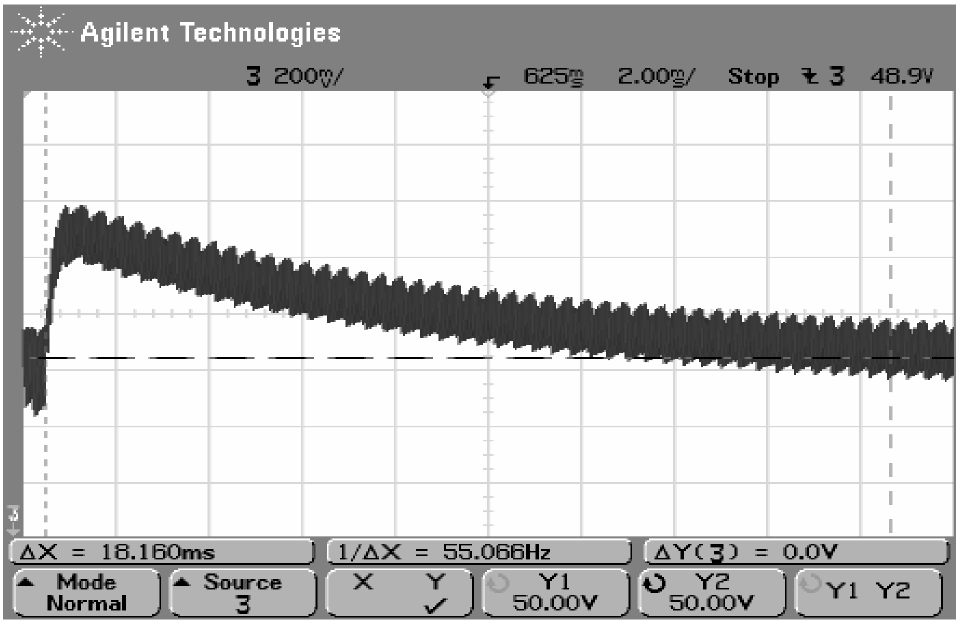

Figure 72 Load voltage characteristic for the load change (Oscilloscope result).

From oscilloscope measurement the settling time is measured as 18.16 ms and the overshoot is measured as 580 mV.

Step-32: "Manual Settings" button is pressed to set the line regulation time and value. The following settings are entered on "Converter Design" GUI:

- R (Load): 100 Ω
- Reference Change: Final reference = 0, Change time = 1 s
- Load Commutation: Final Load = 0, Change time = 1 s
- Line Commutation: Check "DC" Line Commutation
    - Amplitude = 5, Change time = 0.1 s

Step-33: "Closed Loop Simulation" button is pressed to start the simulation. The following output voltage waveform is obtained:

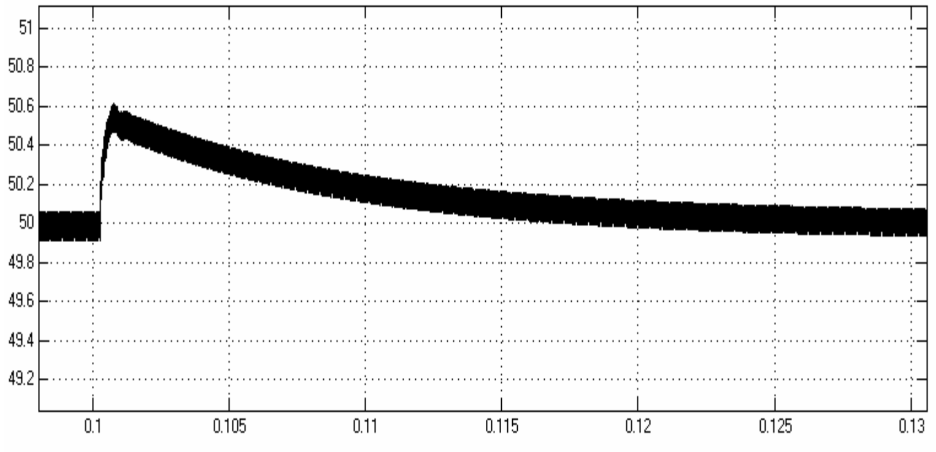

Figure 73 Simulation result of the boost converter load characteristics at DC line change (at t = 0.1 s 5 V DC is added to the DC line input 30 V).

In the simulation the input voltage is changed from 30 V to 35 V. From simulation result the settling time where the output voltage decreases to 50 V is measured as 19 ms, and the maximum overshoot is measured as 0.6 V.

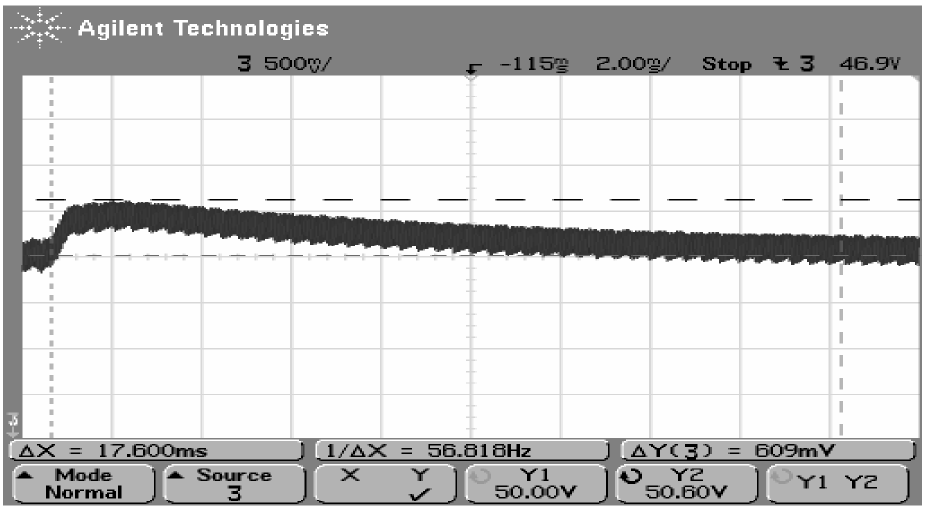

Figure 74 Load voltage characteristic for the line voltage change (Oscilloscope result).

From the oscilloscope measurement the settling time is measured as 17.6 ms and the overshoot is measured as 609 mV.

Step-34: "Manual Settings" button is pressed to set the line regulation time and value. The following settings are entered on "Converter Design" GUI:

- Reference Change: Final reference = 0, Change time = 1 s
- Load Commutation: Final Load = 0, Change time = 1 s
- Line Commutation: Check "AC" Line Commutation
    - Amplitude = 2.3, Frequency = 50 Hz, Change time = 0.02 s

Step-35: "Closed Loop Simulation" button is pressed to start the simulation. The following output voltage and current waveforms are obtained:

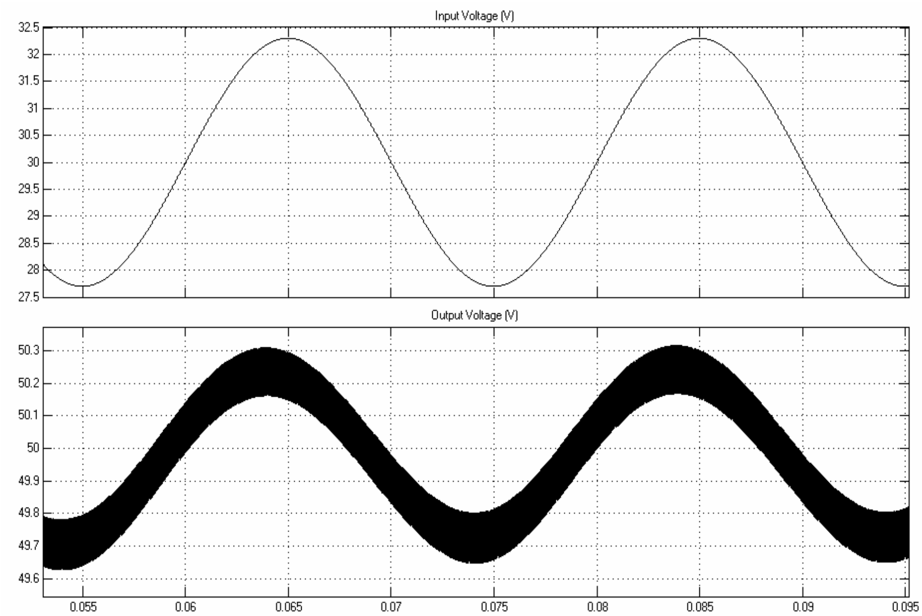

Figure 75 Simulation result of the boost converter load characteristics at AC line change (at t = 0.02 s 2.3 V peak AC is added to the DC line input 30 V).

In the simulation, 4.6 V peak-to-peak AC voltage is added to the 30 V input voltge. From simulation result 660 mV peak-to-peak output voltage change is observed.

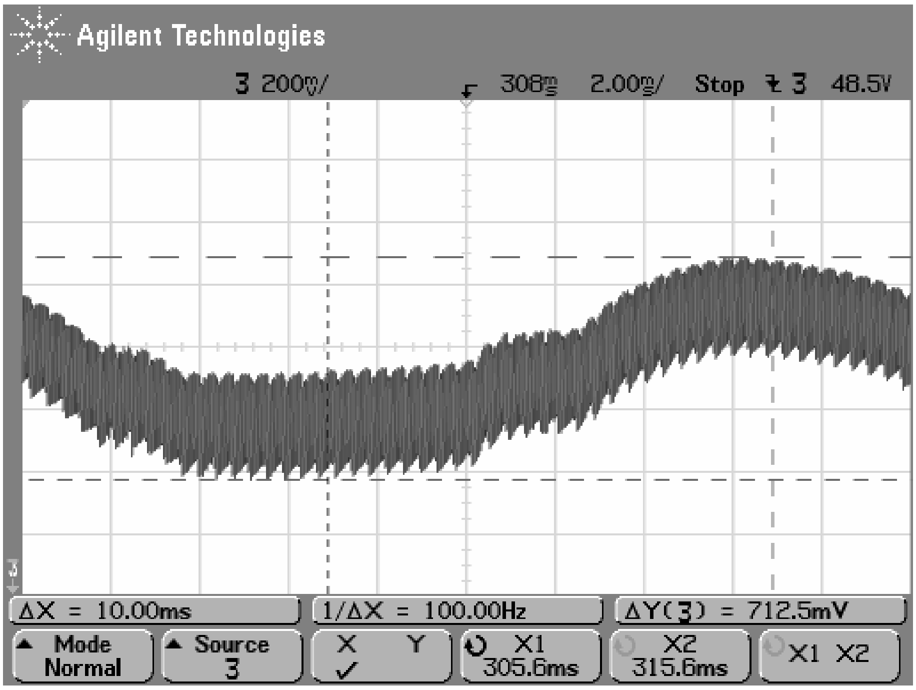

Figure 76 Boost converter load characteristics at AC line change (4.6 V peak-to-peak AC is added to the DC line input 30 V).

From oscilloscope measurement 712.5 mV peak-to-peak output voltage change is observed.

CHAPTER 7

EXPERIMENTAL PROCEDURE

7.1 Object of the Experiment

In this experiment the open loop and closed loop dynamic behaviour of the boost converter will be investigated. In the open loop part of the experiment how the losses in the components effects the convertion ratio will be investigated. Also how ESR value of the output capacitor effects the output voltage ripple will be investigated. Then in the discontinuous conduction mode of operation the effects of the paracitic capacitors on the MOSFET and diode will be discussed. In the second part of the experiment the closed loop performance of the converter will investigated. For this purpose three performance experiments will be performed. First the output voltage behaviour of converter against load change, then behaviour against DC input voltage change and lastly AC input voltage change will be investigated.

7.2 Theory of Operation

7.2.1 Seady State Continuous Conduction Mode

Boost converter is a DC-DC converter that steps up the dc voltage from its fixed low level to a desired high level. Its circuit topology is given in the Figure 77.

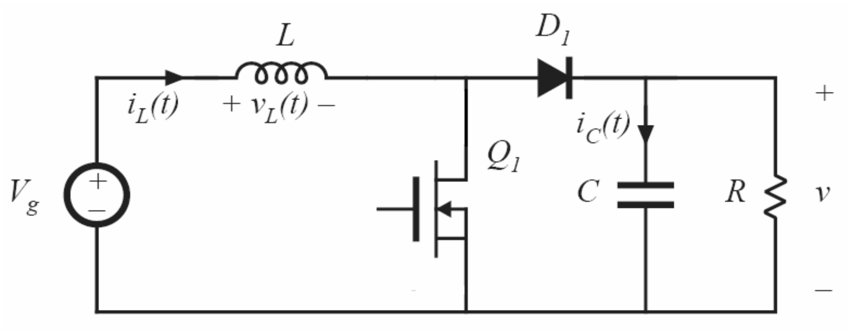

Figure 77 Boost converter.

When the swtch S is closed the differential equation for the inductor current, for $0 \leq t \leq T_{ON} = DT$, is:

$$I_{L,\max} = \frac{V_S}{L} DT + I_{L,\min}$$

Defining the change in the current from its minimum to maximum value as the peak-to-peak current ripple ΔI_L, the above equation yields an expression for ΔI_L as:

$$\Delta I_L = I_{L,\max} - I_{L,\min} = \frac{V_S}{L} DT$$

As soon as the inductor current reaches its maximum value, the switch is opened. The inductor current now begins to supply the load current and charge the capacitor. The corresponding differential equation for $T_{ON} \leq t \leq T$ is [7]:

$$L \frac{di_L(t)}{dt} = V_S - V_O$$

The solution of this equation yields

$$i_L(t') = \frac{V_S - V_O}{L}(t - DT) + I_{L,\max}$$

As per this equation, the inductor current decreases linearly from its maximum value at t = T_{ON} to its minimum value as t = T, such that [7]:

$$I_{L,\min} = \frac{V_S - V_O}{L}(1-D)T + I_{L,\max}$$

The peak-to-peak current ripple is:

$$\Delta I_L = I_{L,\max} - I_{L,\min} = -\frac{V_S - V_O}{L}(1-D)T$$

Two formulas found for the current ripple ΔI_L must be the same. Equating the two equations, the following is obtained:

$$\frac{V_S}{L}DT = -\frac{V_S - V_O}{L}(1-D)T$$

This equation upon simplification yields:

$$V_O = \frac{V_S}{1-D}$$

The inductor current is sketched as shown in the Figure 78. It also represents the source current.

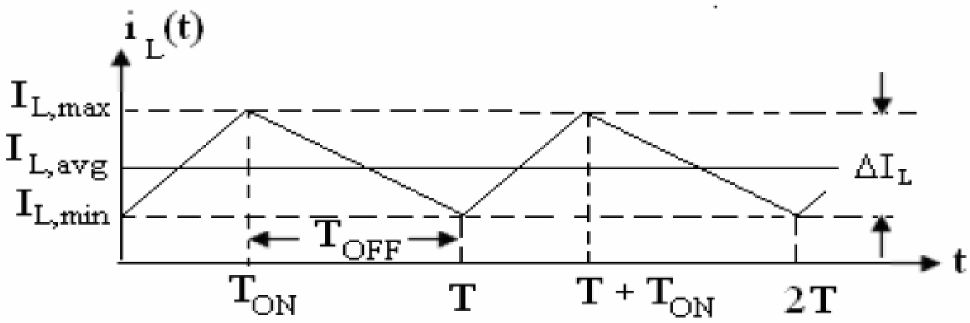

Figure 78 Inductor and the source currents.

The capacitor current waveform is shown in the Figure 79.

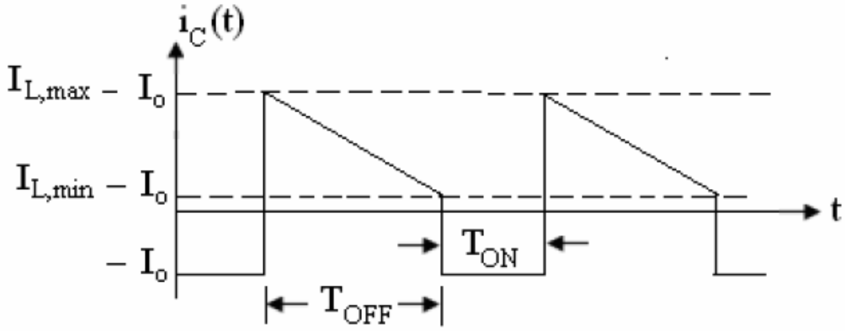

Figure 79 Current through the capacitor.

The current waveform helps to determine the change in the voltage across the capacitor. During the time the switch is closed, the charge on the capacitor is decreasing because the capacitor is supplying the current to the load. The change in the charge is:

$$\Delta Q = -I_O T_{ON} = -\frac{V_O}{R} DT$$

The decrease in the charge will result in a decrease of the capacitor voltage from its average value of V_O. Therefore, the magnitude of the change in the capacitor voltage is:

$$|\Delta V_O| = \frac{\Delta Q}{C} = \frac{V_O}{RC} DT$$

During the time the switch is open, the component of the inductor current that flows through the capacitor will increase the capacitor voltage by the same amount. Hence, if the capacitor voltage ripple is defined as the ratio of the increase in the capacitor voltage from its average value, it can be expressed as:

$$\frac{\Delta V_O}{V_O} = \frac{DT}{RC} = \frac{D}{RCf}$$

The peak-to-peak voltage ripple for the boost converter will be twice of that given in the above equation. This equation is viewed as one-sided voltage ripple.

7.2.2 Steady State Discontinuous Conduction Mode

When the diode conducts, its current is identical to the inductor current $i_L(t)$. If minimum inductor current is positive, then the diode is positive biased for the entire subinerval $DT_S < t < T_S$, and the converter operates in the continuous conduction mode. So the conductions for operation of the boost converter in the continuous and discontinuous conduction modes are:

$$I > \Delta i_L \quad for \quad CCM$$
$$I < \Delta i_L \quad for \quad DCM$$

Substitution of the CCM solutions for I and Δi_L yields:

$$\frac{V_g}{D'^2 R} > \frac{DT_S V_g}{2L} \qquad \text{for CCM}$$

This equation can be rearranged to obtain:

$$\frac{2L}{RT_S} > DD'^2 \quad \text{for CCM}$$

In the DCM there is low frequency parasitic oscillation on the switch voltage and the input current. This is because at the moment the inductor current becomes zero, the switch voltage should adopt the input votage, and the input current should remain zero. Nevertheless, for real switches, a network, consisting of parasitic capacitances C_{OSS} of the the switch and C_D of the diode, and the inductor L (Figure 52) starts the oscillating at that instant [12].

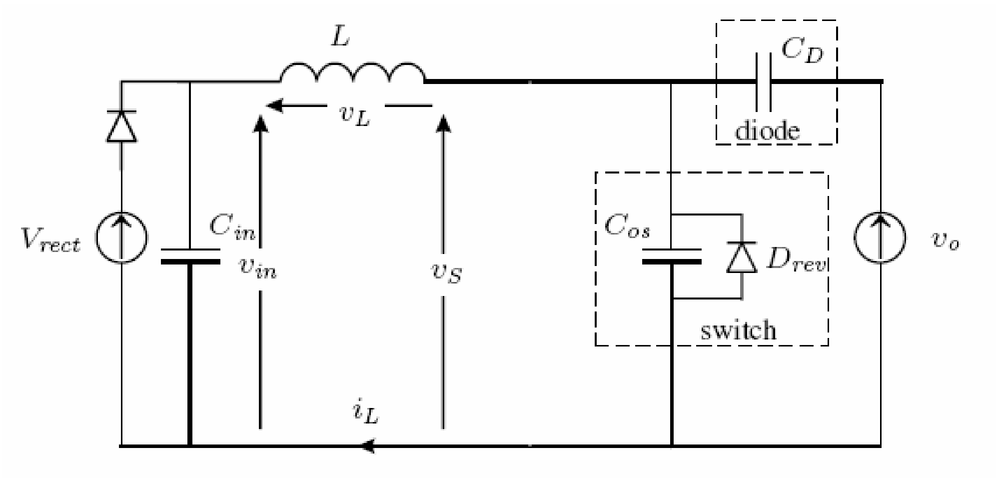

Figure 80 Parasitic network causing oscillations [12].

The switch voltage oscillation is described approximately as [12]:

$$V_S(t) = V_{in} + (V_O - V_{in})\cos(w_n(t - t_2))$$

Where:

$$w_n = \frac{1}{\sqrt{LC_n}}$$

The capacitance C_n, in these expressions is equal to the parallel connection of the switch capacitance and the diode capacitance [12].

The followings are boost converter switch and diode parasitics taken from their datasheets;

- C_{oss} of MOSFET (IRF530) is equal to 210 pF
- C_D of diode (DSS16-01A) is equal 140 pF

7.3 Components of the Experiment System

Experiment system contains two major parts, software part, named "Converter Design" GUI, and hardware part. The brief explanations of these parts are given below.

7.3.1 "Converter Design" GUI

In MATLAB Workspace, by typing "Converter_Design" GUI will be opened (Figure 81). This guide will help the user to design the converter, obtain small signal model, frequency responses, closed loop/open loop transfer functions and run simulations using MATLAB-Simulink. An instruction related with GUI is given in this section. Before starting, the following "Notes" have to be read. They include crucial information to be known before starting to use GUI.

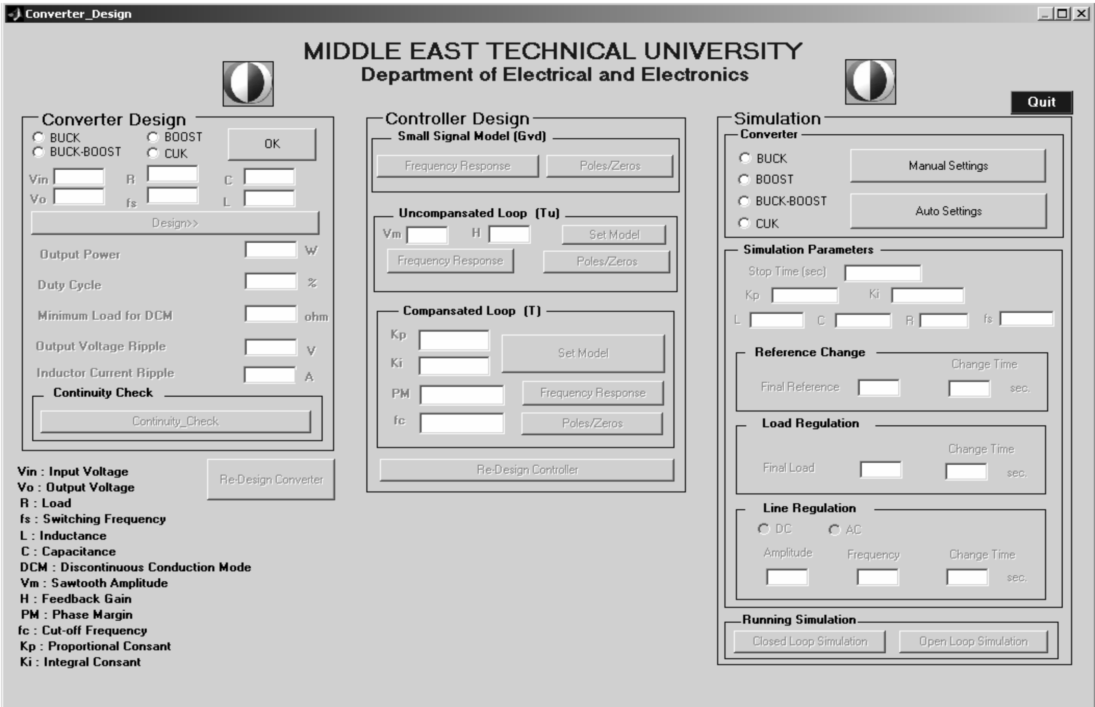

Figure 81 “”Converter Design” GUI.

Note-1: All actions can be performed by pressing button on the GUI. GUI is designed in a hierarchic structure that enables the user to pass to the right step by enabling-disabling the other buttons on the screen.

Note-2: “Reset” buttons are used to end the application and return to the starting. “Re-design” button enables the user to return to the previous step for any undesired condition occuring in data entry to the GUI.

Note-3: All figures will be closed when the GUI is ended and reset for starting.

Note-4: “Set Model” buttons are used to generate the related transfer functions.

Note-5: If the user does not select a converter type and presses “OK” and/or “Press” button, “Buck” converter will be automatically selected

Not-6: “Frequency Response” and “Poles/Zeroes” buttons will return to passive when they are pressed. So for user future observation, they are not to be closed during the application.

The following GUI special sections are given to provide general information about usage.

Converter Type: Converter type is selected in this section. The type shall be one of those given below:

- Buck Converter
- Boost Converter
- Buck-Boost Converter
- Cuk Converter

One of the converter types should be selected to be able to pass to the other steps.

Design Inputs: They are needed to design the converter design outputs. They are:

- V_{in} (Converter Input Voltage)
- V_o (Converter Output Voltage)
- R (Load)
- f_s (Switching Frequency)
- L (Inductance)
- C (Capacitance)

Design Outputs: Design outputs are calculated by GUI in accordance with the design inputs specified before. This step is performed by pressing “Design” button. This button activates “design.m” M-file that contains steady-state design formulas of the related converter. The design outputs are:

- Output Power
- Duty Cycle
- Minimum Load for Discontinuity

- Output Voltage Ripple
- Inductor Current Ripple

Continuity Checking: This step is used to control whether the designed converter is in continuous conduction mode or not.

Models: Some models are generated to be able to generate PI compensator parameters in closed-loop control. They are:

- **Small-Signal Model (G_{vd}):** Transfer function between duty cycle and converter output voltage.
- **Uncompensated Loop Model (T_u)**: Closed-loop transfer function with no compensation
- **Compensated Loop Model (T):** Closed-loop transfer function with compensation

Each model has its special section on the GUI. The related plots of the models can be generated by pressing “Frequency Response” and “Poles/Zeroes” buttons placed in these special sections.

Frequency Response: “Frequency Response” buttons are used for easy investigation of the related transfer function frequency response by the user. Which transfer function frequency response the user is investigating can be seen under the name of the related section. By pressing “Frequency Response” button, the user can view phase and gain margins, cut-off frequency and low/high frequency characteristics of the related model. On the generated figure, the user can select a point by using the cursor. The related frequency and magnitude/phase can be seen on the screen.

“Frequency Response” figures that can be generated are listed below:

- Frequency Response for Small-Signal Model (G_{vd})
- Frequency Response for Uncompensated Loop Model (T_u)
- Frequency Response for Compensated Loop Model (T)

Another “Frequency Response” plot is generated during design stages. This is generated when one of the “Frequency Response” buttons on the GUI is pressed. Its main function is to plot all the frequency responses generated during design on a single figure. It is very useful for the user to see what actions are performed at the end of the design.

Poles/Zeroes: “Poles/Zeroes” buttons are used for easy investigation of the related transfer functions’ poles and zeroes by user. Which transfer functions’ poles and zeroes the user is investigating can be seen under the name of the related section. When these buttons are pressed, a “Pole-Zero map” appears on the screen. On the map, the user can see all poles and zeroes and make point selection by the cursor. The related poles and zeroes values (real and imaginary parts) can be seen on the screen.

“Poles/Zeroes” figures (maps) that can be generated are listed below:

- Poles/Zeroes for Small-Signal Model (G_{vd})
- Poles/Zeroes for Uncompensated Loop Model (T_u)
- Poles/Zeroes for Compensated Loop Model (T)

Compensator Inputs: Some design inputs are needed to calculate a specific compensator for “T_u” (Uncompensated Loop Model). They are:

- **Vm** : Amplitude of the sawtooth control signal.
- **H** : Feedback gain.

Controller Inputs: Some design inputs are needed to calculate specific compensator parameters for “T” (Compensated Loop Model). They are:

- K_p: Proportional Gain
- K_i: Integral Gain

Converter Simulation: By using “Auto Setting” and “Manual Setting” options, the user can simulate the designed converter type with MATLAB-Simulink. “Auto Setting” button is used to transmit all calculated design parameters to the simulation program. “Manual Setting” button is for manual regulation. The user can run another converter simulation after one is terminated either manually or automatically.

Quit: “Quit” button is the only way to quit the application.

7.3.2 Specification of the Boost Converter

The general view of the boost converter test box is given in Figure 82. It contains open and closed loop control buttons and probes for external measurements. The functions of each section are shown in Figure 82.

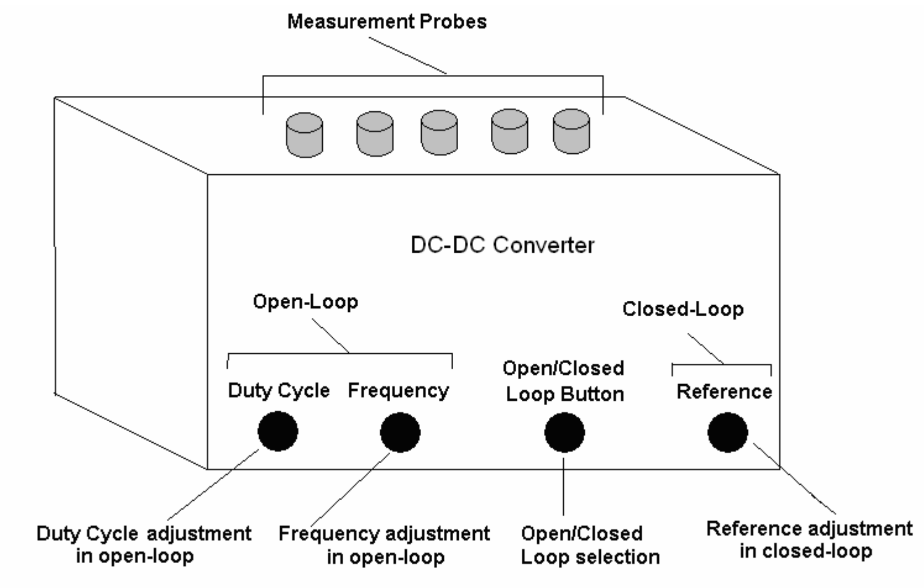

Figure 82 General view of the dc-dc converter test box.

The specification of the boost converter test box is given in Table 2.

Table 2 Boost converter test box specification

Input voltage	10 V-30 V
Minimum Output Load	30 Ω
Inductor	220 µH ($R_{internal}$ = 0.05Ω)
Capacitor	100 µF (ESR = 0.15)
Operation Frequency	7.7 kHz - 58 kHz
Maximum Duty Cycle	70 %
Maximum Output Power	100 W

The general block diagram of the circuit is shown in Figure 83 and the circuit layout is shown in Figure 84. The circuit consists of three parts: power stage, PWM stage and compensator stage.

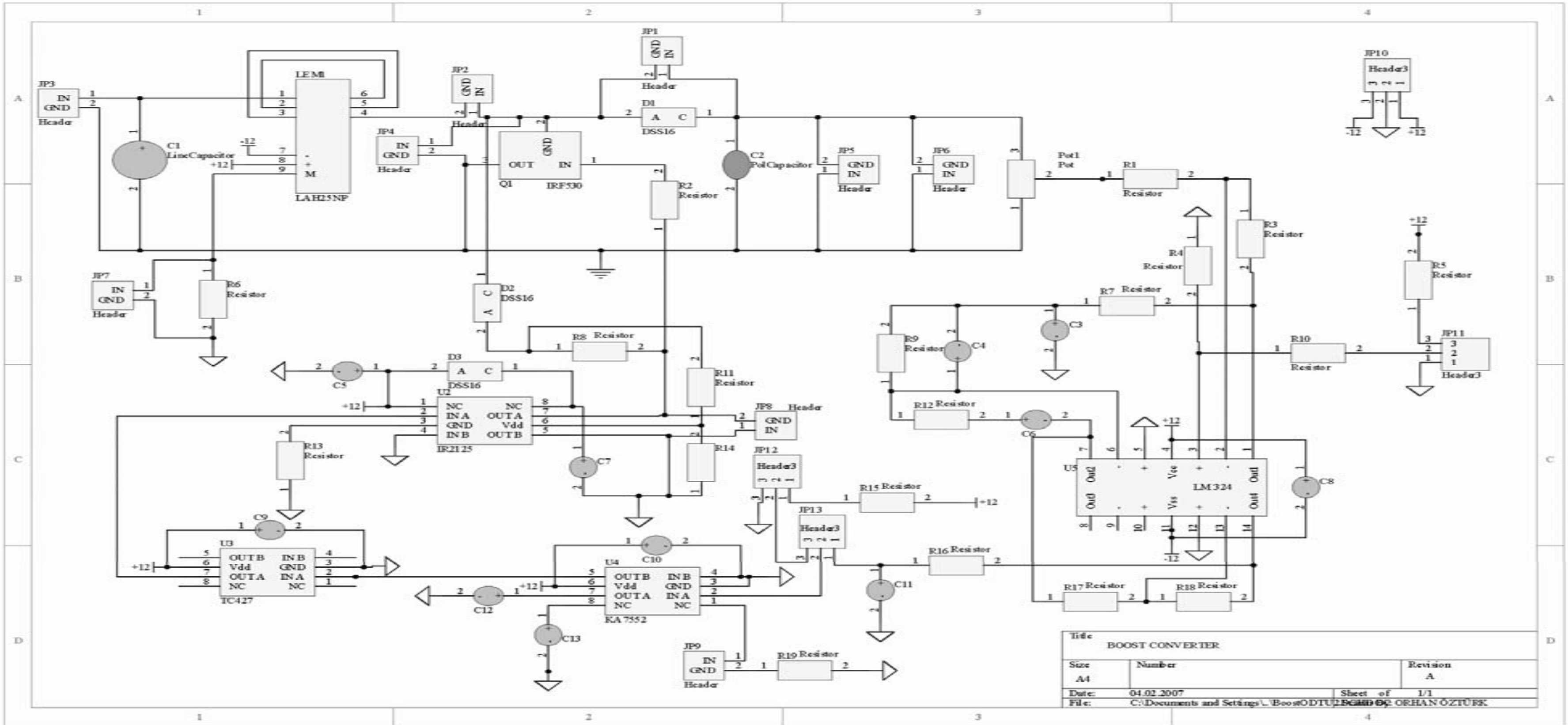

Figure 83 Hardware overview

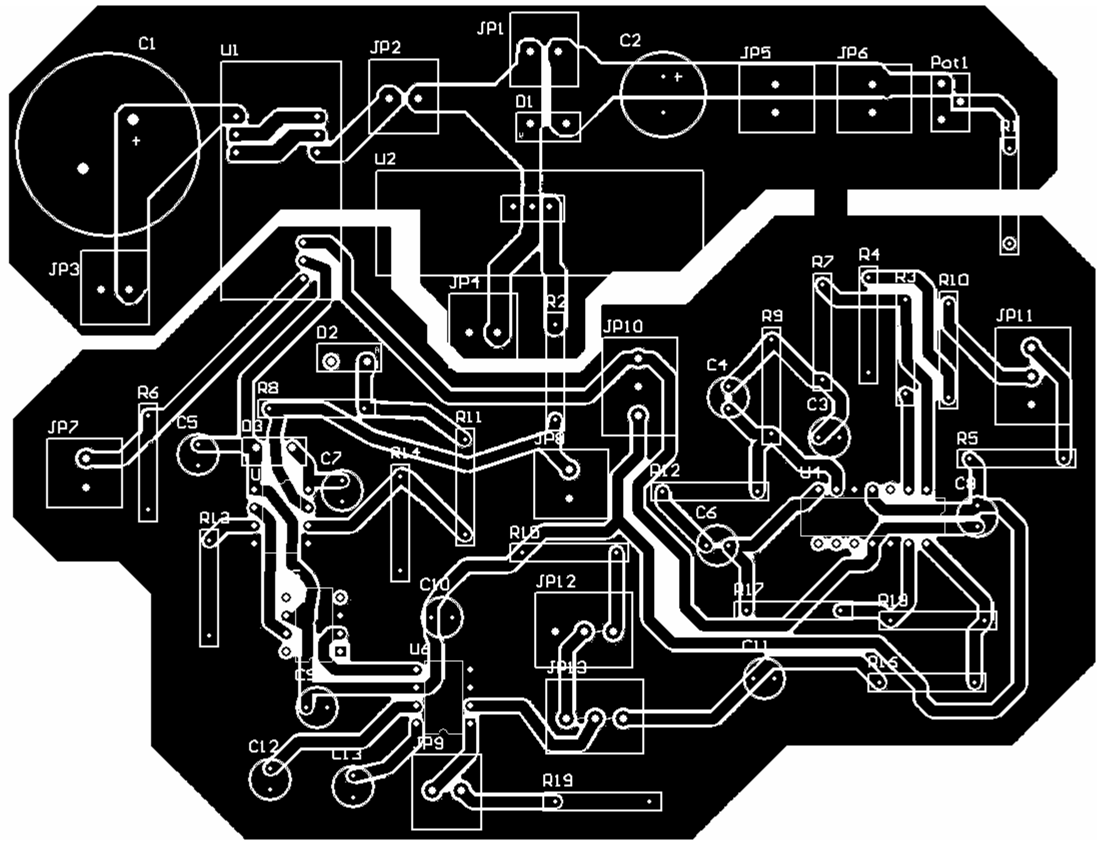

Figure 84 Circuit layout (Bottom layer).

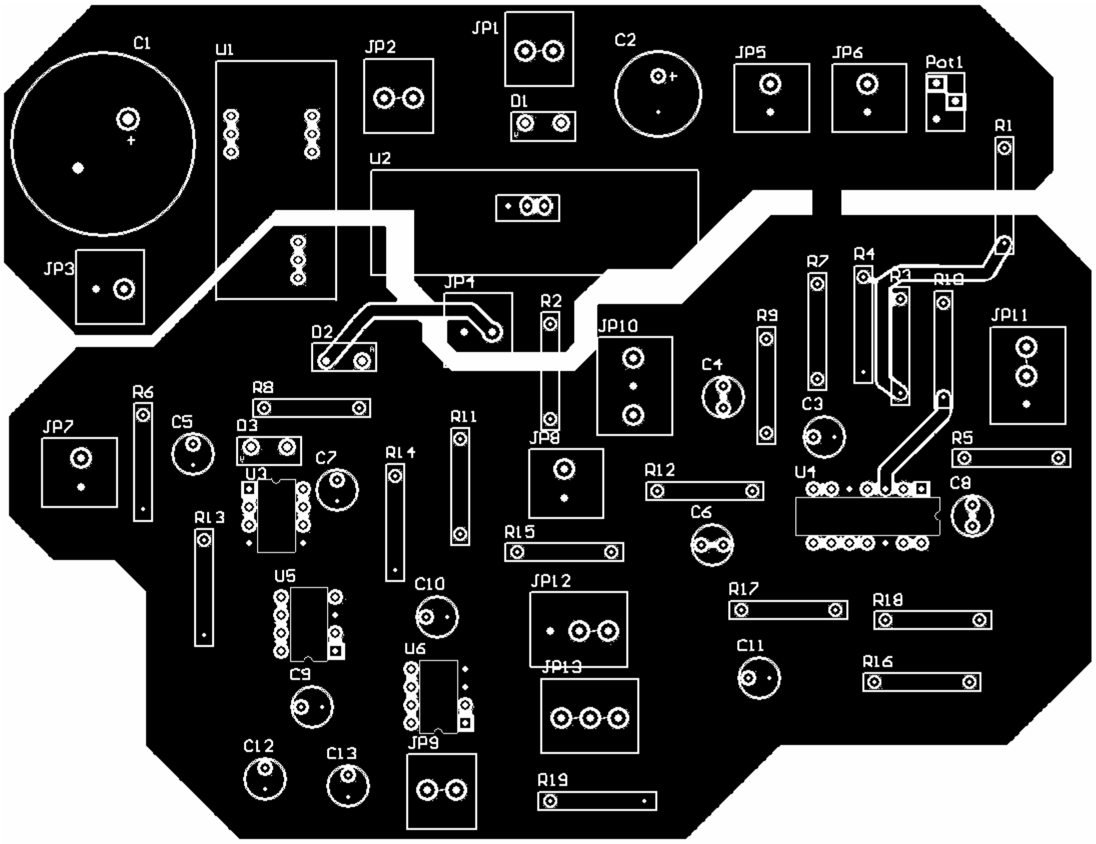

Figure 85 Circuit layout (Top layer).

The power stage consists of a boost converter and IR2125 gate driver. In the conpensator stage op-amps are used to design PI controller. In the PWM stage KA7552 IC is used to produce PWM signals.

In the power stage the input voltage is adjustable up to 30 V. The inductor is constant and has the value of 220 μH; also the capacitor is constant and is 100 μF. The minimum load connected to the output should not be smaller than 30 Ω for safety.

In the compensator stage OP1 (LM324 is Quad op-amp these four opamp are identified as OP1, OP2, OP3 and OP4) is the difference amplifier. The reference voltage that is adjusted with JP11 is extracted from output voltage that is scaled with POT2. OP2 opamp is used as PI compensator. The transfer function of compensator is:

$$G(s) = -\frac{R_{12}}{R_9}\frac{\left(R_{12}C_4 s + 1\right)}{R_{12}C_4 s}$$

From this equation the PI parameters are:

$$Kp = \frac{R_{12}}{R_9}$$

$$Ki = \frac{1}{R_9 C_4}$$

In this experiment the P nd I constans are:

$K_p = 7.35$
$K_i = 890$

Because a negative voltage level is obtained at the output of "OP2" opamp, another opamp, "OP3" is used as an inverting amplifier which has "$-R_{18}/R_{17}$" convertion ratio.

JP13 switch selects the operation of the circuit, if it is in position connected to the OP3 output the circuit operates in closed loop operation, if it is in position connected to the JP12 the circuit operates in open loop operation. JP12 adjusts the duty cycle of the PWM output in the open loop operation. JP9 adjusts the frequency of the PWM, the frequency is adjustable both in the open loop and closed loop operations.

As gate driver in the circuit IR 2125 is used. It is a high side gate driver that can be used in the low side applications. This driver also has the cycle-by-cycle over current protection feature.The components used in the boost converter are listed below in the table.

Table 3 Boost converter part list

Component	**Referance**	**Qty**	**Description**	**Part Number – Manufacturer**
Diode	D1, D2, D3	3	I_{FAV} = 16A, V_{RRM} = 100V, V_F = 0.64 V, C_T = 150 pF	IXYS, DSS16-01A
MOSFET	Q1	1	V_{DSS} = 100 V, $R_{DS(ON)}$ = 0.64 Ω, I_D = 14 A, C_{oss} = 220pF	International Rectifier, IRF 530
Inductor	JP2	1	220 μH, 5 A	Coilcraft, PCV-2-224-05,
Capacitor	C1	1	1000 μF, 100 V	Kendeil
	C2	1	100 μF, 100 V	G.Luxon
	C3, C4, C5, C6, C7, C8, C9, C10, C11	9	1 μF, 50 V	Su'scon
	C12	1	3.3 nF, 100 V	
	C13	1	2.2 nF, 100 V	
IC	U2	1	Current limiting single channel driver	International Rectifier, IR2125
	U3	1	MOSFET Driver	Microchip, TC 427
	U4	1	PWM Controller	Samsung, KA7552
	U5	1	Quad Opamp	National Semiconductor, LM324
Resistors	R1, R3, R4, R10, R17	5	100 kΩ, 1/4 W	
	R2	1	10 Ω, 1/4 W	
	R5	1	20 kΩ, 1/4 W	

Table 3 (continued)

Component	Refera nce	Qty	Description	Part Number – Manufacturer
Resistors	R6	1	332 Ω, 1/4 W	
	R8	1	22 kΩ, 1/4 W	
	R18, R14	1	22 kΩ, 1/4 W	
	R13	1	620 kΩ, 1/4 W	
	R19	1	160 Ω, 1/4 W	
	R15	1	8.2 kΩ, 1/4 W	
	R11	1	1 kΩ, 1/4 W	
	R9	1	8.2 kΩ, 1/4 W	
	R12	1	1.1 kΩ, 1/4 W	
Potantiometer	JP12	1	1 kΩ	
	JP9, JP11	1	10 kΩ	

7.4 Apparatus

The following apparatus are needed to maintain the boost converter experiment.

Table 4 Apparatus used in experiment

Component	Quantity	Specification
Boost Converter	1	Given in table 2
Oscilloscope	1	Agilent
DC Power Supply	2	30 V 6 A
Rheostat	2	420 Ω 11 A
PC	1	Standart (“Converter Design” tool installed)

7.5 Experimental Procedure

7.5.1 Open Loop Characteristics

This experiment is intended to show the open loop behaviors of the boost converter operate in continuous and discontinuous conduction mode. In this experiment the waveforms of MOSFET voltage, diode voltage, inductor current and output voltage wavefoms will be investigated for different duty cycle, frequency and load values.

7.5.1.1 Procedure

1- Set-up the following hardware configuration (Figure 86).

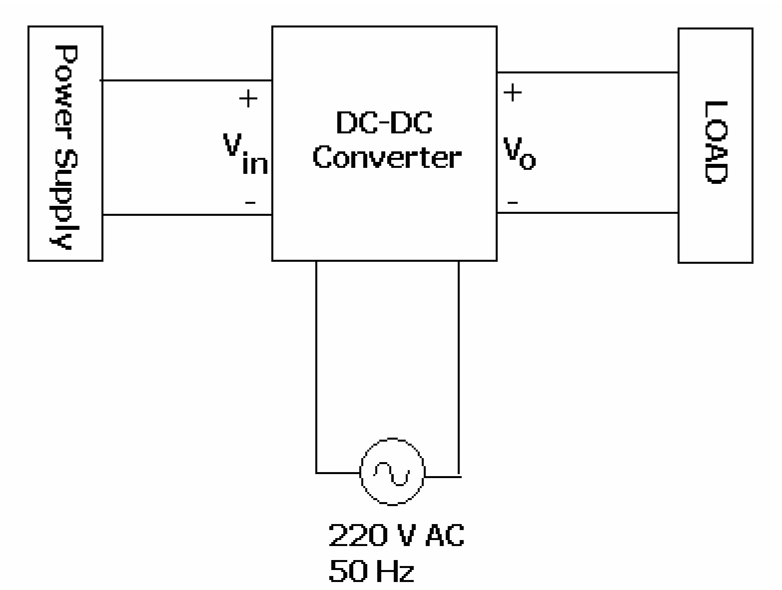

Figure 86 Converter hardware set-up (open-loop).

Turn the OPEN/CLOSED LOOP switch on the converter to OPEN LOOP position. Set-up the power supply to 30 V DC and make sure that it is turned-off before starting. Adjust the rheostat to 50 Ω. Turn on the power supply.

2- By using FREQUENCY button, adjust the switching frequency to 20000 Hz. By using DUTY CYCLE button, adjust the duty-cycle to 40 %. Connect the oscilloscope probe to the related measurement probes of the boost converter test box and observe waveforms of the MOSFET voltage, diode voltage, inductor current, output voltage and output voltage ripple. In the “Converter Design“ tool enter the values used in the experiment and observe the steady-state calculation results and simulation results. Measured values are illustrated below.

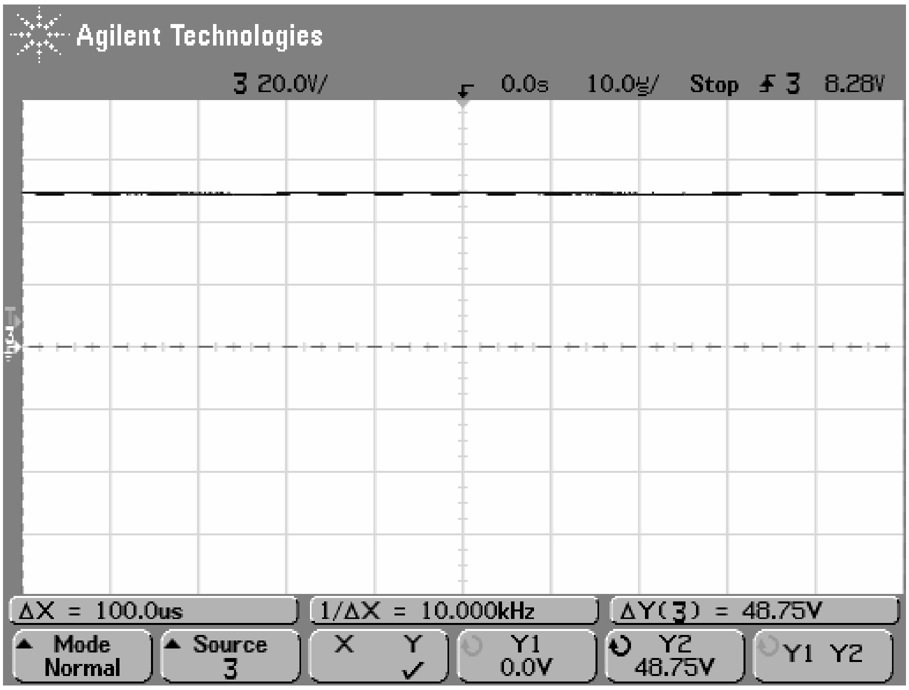

Figure 87 Boost converter output voltage.

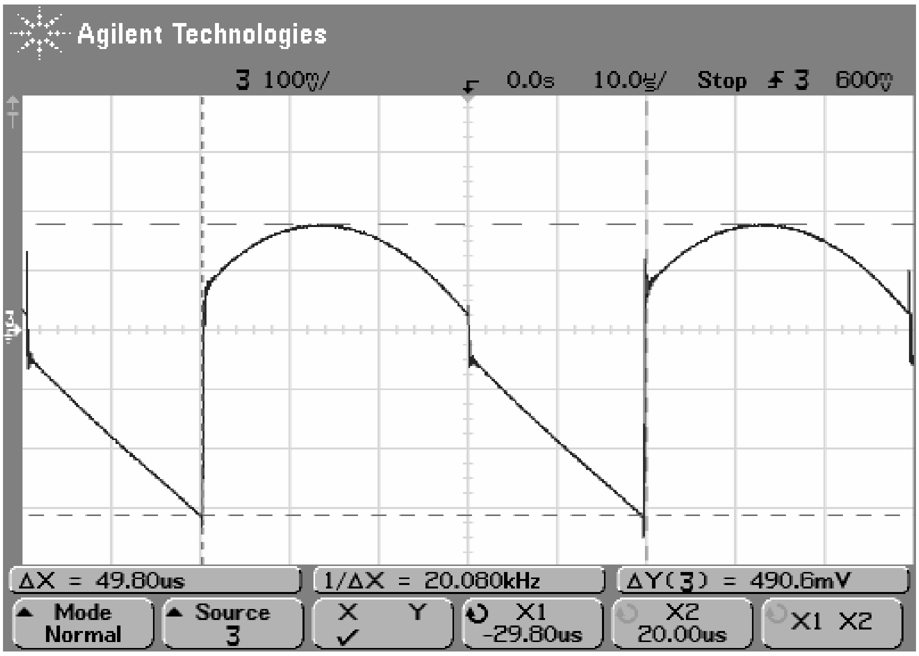

Figure 88 Output voltage in the AC mode of the oscilloscope.

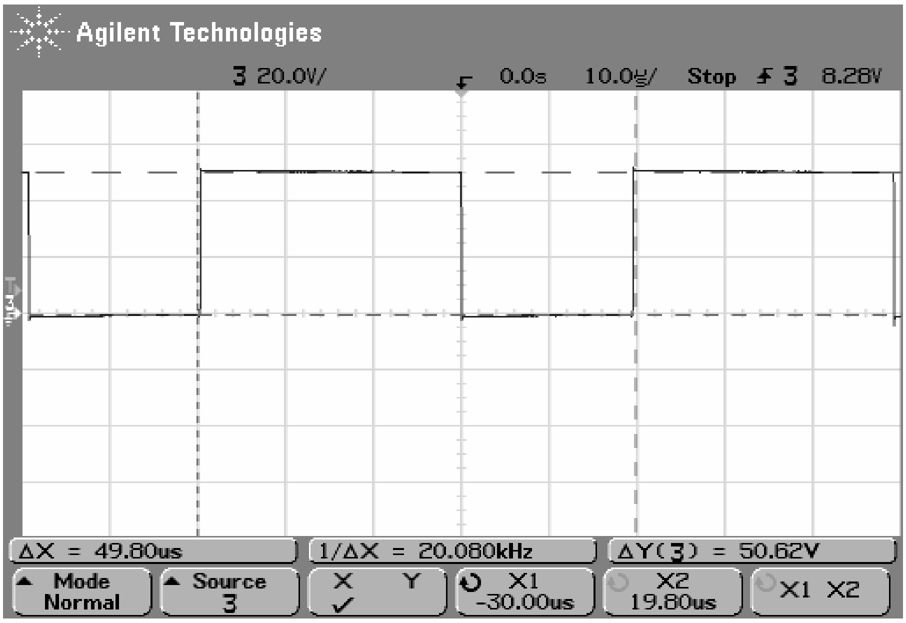

Figure 89 MOSFET voltage, V_{ds}.

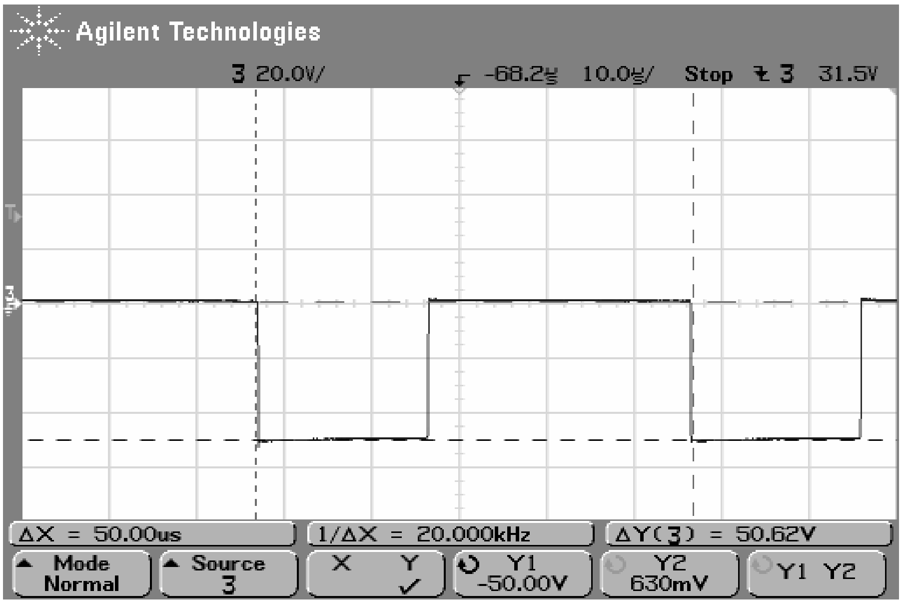

Figure 90 Diode voltage.

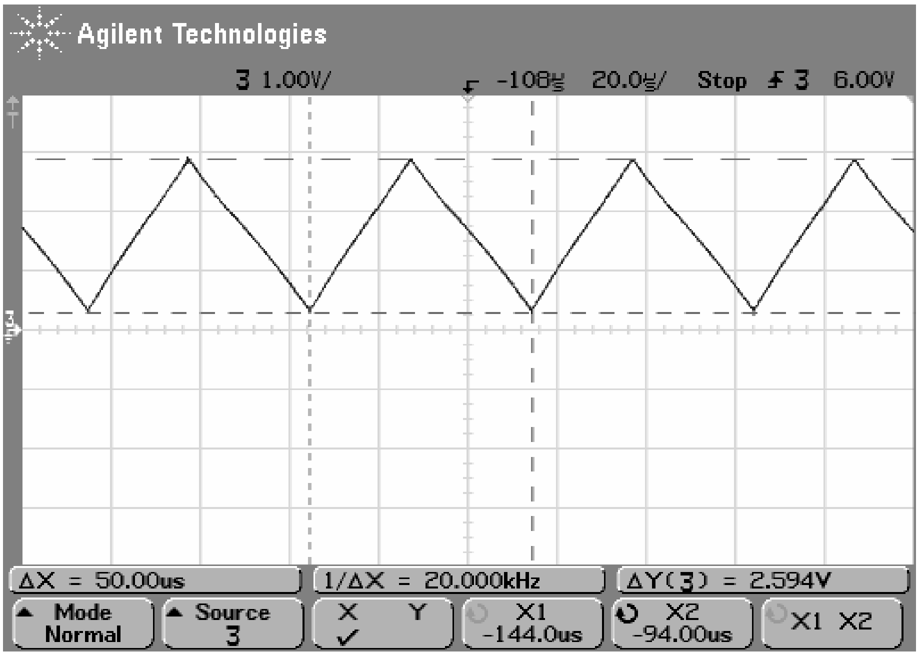

Figure 91 Inductor current.

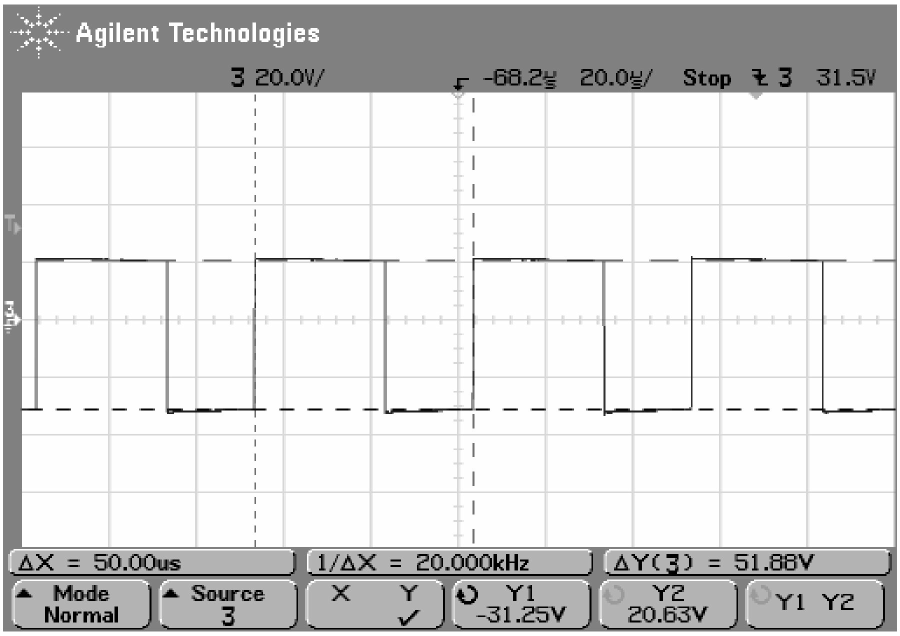

Figure 92 Inductor voltage.

3- Repeat step 2 for 10, 20, 30, 50, 60, 70 % duty cycle.

4- Set the duty cycle to the 40%, set the switching frequency to 50 kHz and observe the output voltage ripple. By using the "Converter Design" tool simulate and observe the results. Measured values for 50 kHz are illustrated below.

5- Repeat step 4 for switching frequency 10, 30 and 40 kHz.

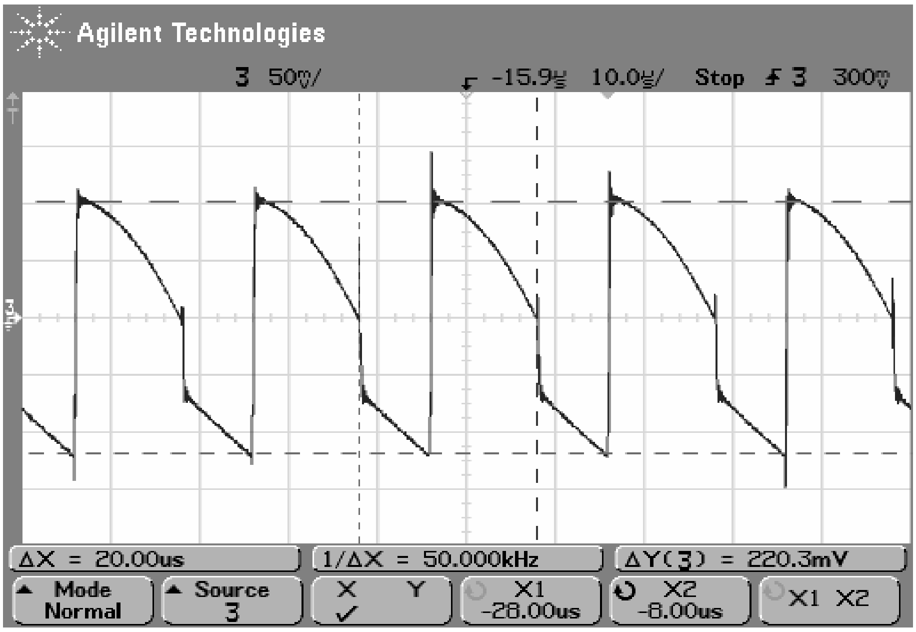

Figure 93 Output voltage in the AC mode of the oscilloscope.

6- Turn off the power supply, disconnect the rheostat from the boost converter test box and by using multimeter adjust the rheostat to the 100 Ω. Connect the rheostat to the test box, turn on the power supply adjust the frequency to 20 kHz. By using oscilloscope observe the MOSFET voltage, diode voltage, inductor current, inductor voltage, output voltage and output voltage ripple. Also observe the low frequency parasitic oscillation on the MOSFET voltage waveform and record the oscillation frequency. The measured values are illustrated below.

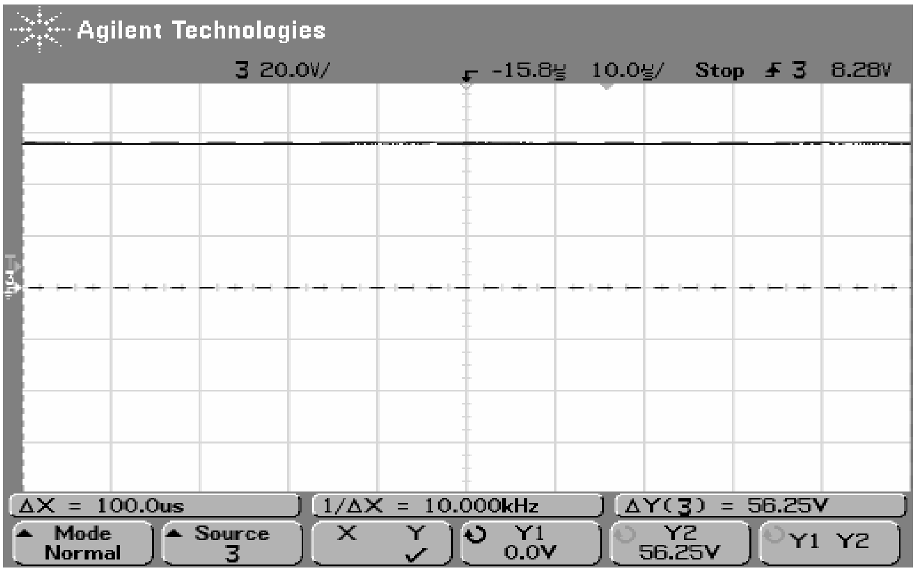

Figure 94 Output voltage (oscilloscope is at DC mode).

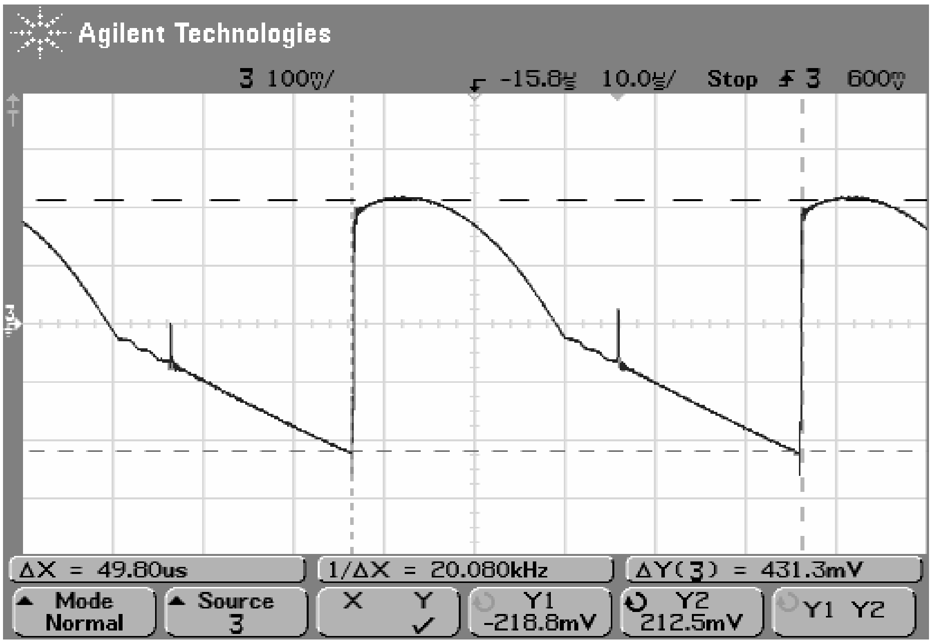

Figure 95 Output voltage in the AC mode of the oscilloscope.

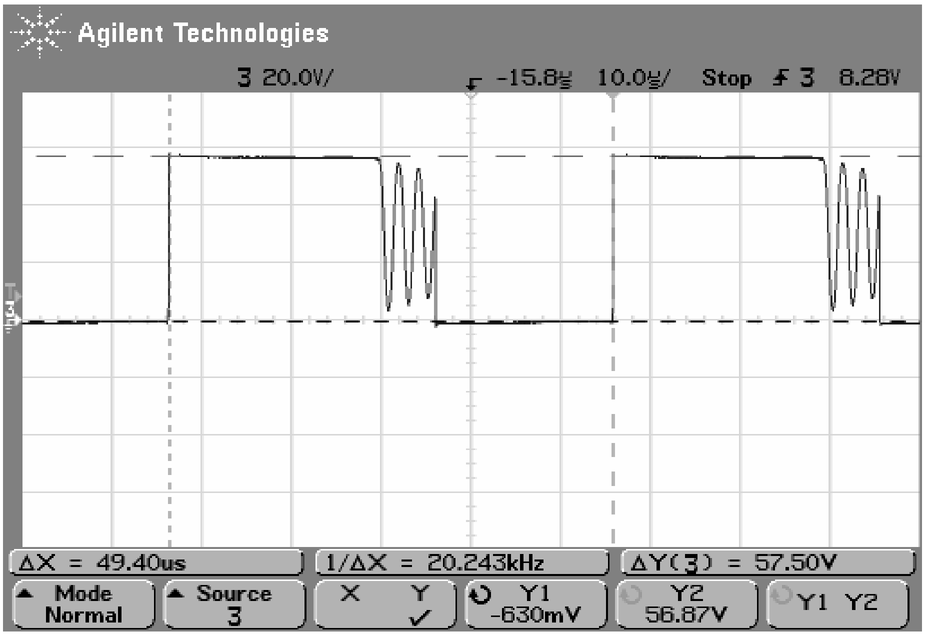

Figure 96 MOSFET voltage, V_{ds}.

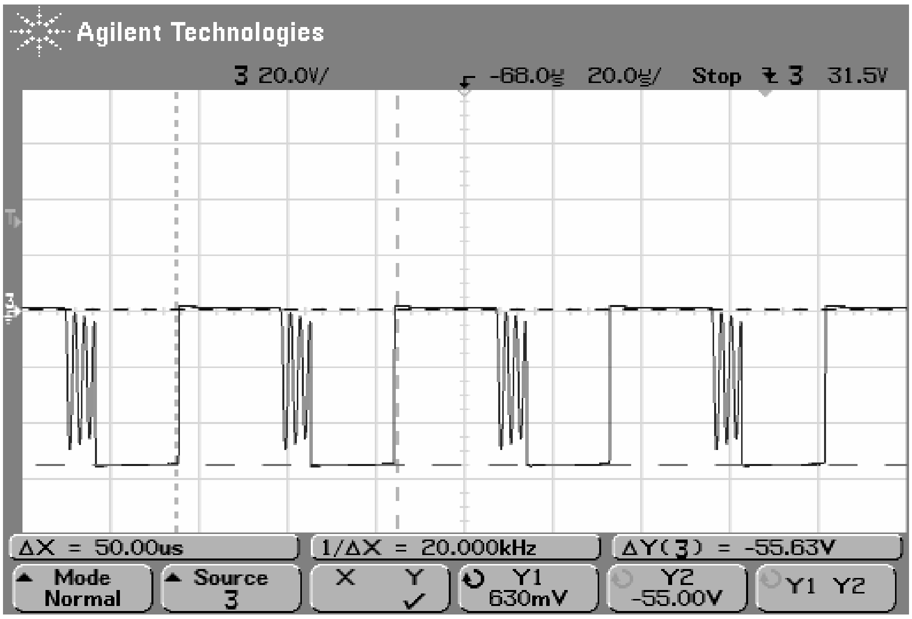

Figure 97 Diode voltage.

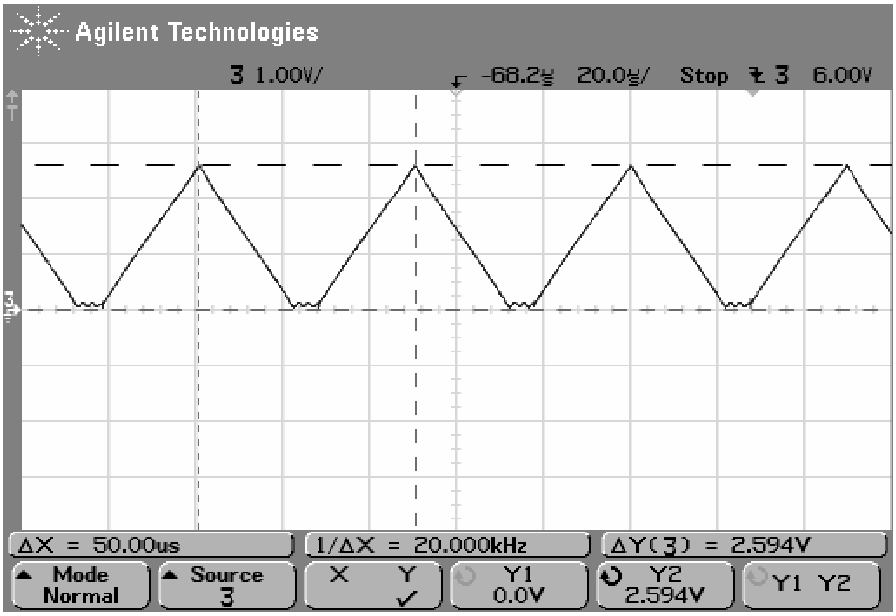

Figure 98 Inductor current.

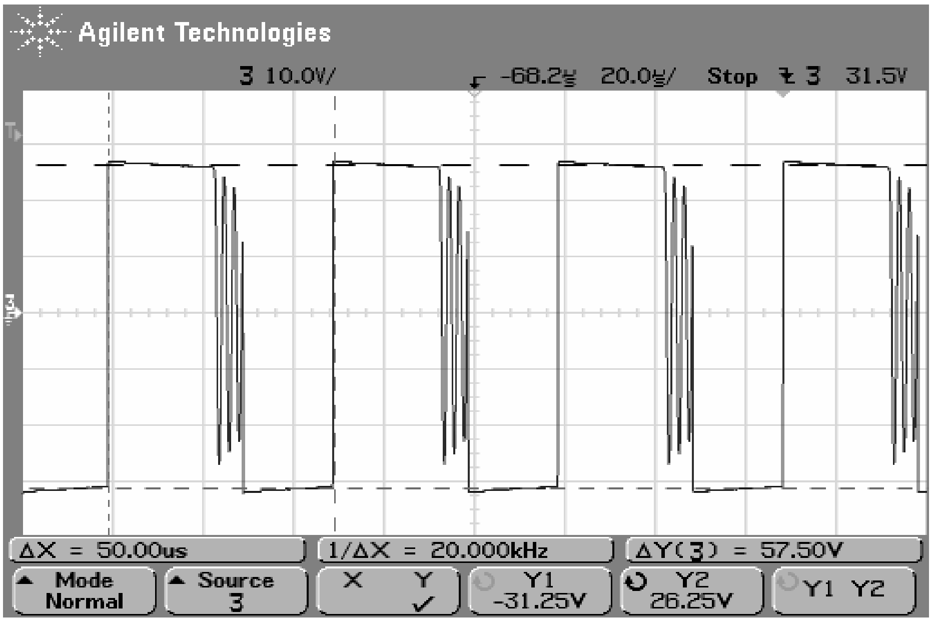

Figure 99 Inductor voltage.

7.5.1.2 Study Questions

1- Comment and compare the output voltage ripple results those found from steady-state formulas and experiment results. What is effect of output capacitor ESR value on the voltage ripple?

2- Plot the output voltage versus duty cycle graph found by steady state formula and experiment results. Comment on the difference between two graphs. Explain the effect of the losses associated with the inductor, capacitor, switch and diode on the output voltage.

3- Explain the effect of switching frequency on the inductor current ripple and the output voltage ripple.

4- Explain the reason of the parasitic oscillation on MOSFET and diode voltage operating in discontinuous conducton mode.

7.5.2 Closed Loop Characteristics

This experiment is intended to show the closed loop behaviors of the boost converter. In this experiment three sub experiments will be performed. First dynamic performance aginst load change, second dynamic performance against DC input voltage change and last dyamic performance against AC nput voltage change.

7.5.2.1 Procedure

1- In the “Converter Design” tool set the following parameters.

Table 5 Closed Loop Simulation Parameters

Reference Change	Final Reference: 30 V	Change Time: 0.2 sec
Load Regulation	Final Load: 200 Ω	Change Time: 0.1 sec
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.2 sec
Line Regulation (AC)	Amplitude: 2.3 V peak ; Frequency: 50 Hz	Change Time: 0.2 sec

Then press the "closed loop simulation" button. After simulation finish observe the dynamic behaviour of the boost converter against load change.

2- Power off power supply, adjust the rheostats to 200 Ω and set-up the following hardware configuration (Figure 100).

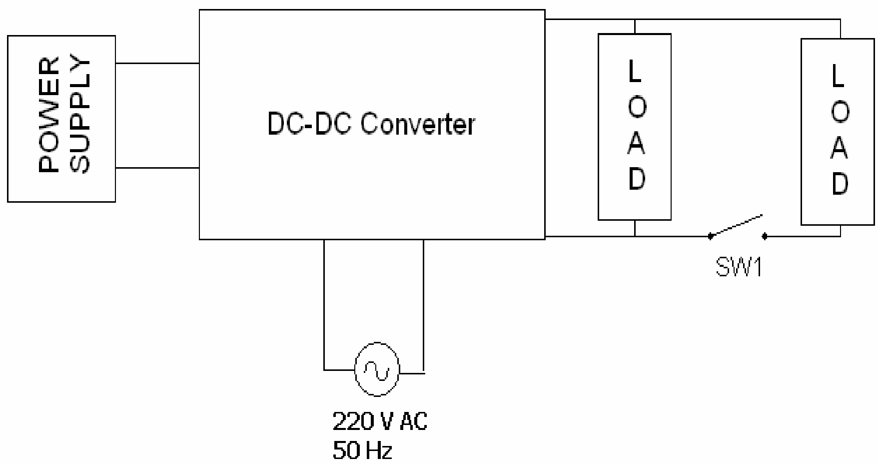

Figure 100 Converter hardware set-up (closed-loop) for load regulation.

Turn the "Open/Closed Loop" switch to cosed loop position turn on the power supply. Adjust the output voltage by changing the "Referance" switch. Before startng the experiment switch SW-1 must be closed and oscilloscope must be connected to read the output voltage. Suddenly open the switch SW-1 so that the load is suddenly changed from 100 Ω to 200 Ω. Record the output voltage load change load. Measured values are illustrated below.

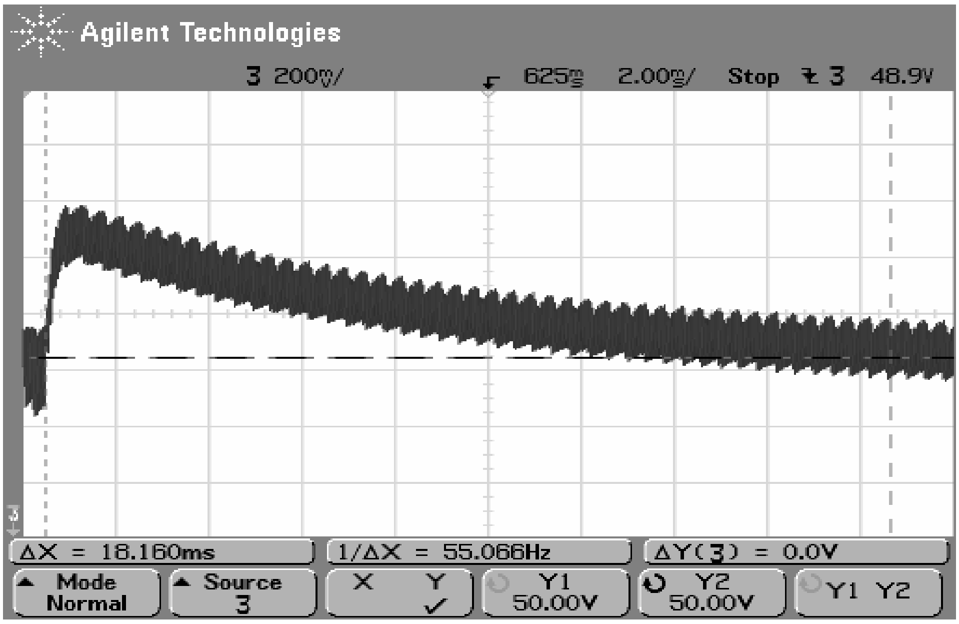

Figure 101 Load voltage characteristic for the load change.

3- In the “Converter Design” tool set the following parameters.

Table 6 Closed Loop Simulation Parameters

Reference Change	Final Reference: 30 V	Change Time: 0.2 sec
Load Regulation	Final Load: 200 Ω	Change Time: 0.2 s
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.1 s
Line Regulation (AC)	Amplitude: 2.3 V peak ; Frequency: 50 Hz	Change Time: 0.2 s

Then press the "closed loop simulation" button. After simulation finish observe the dynamic behaviour of the boost converter against DC input voltage change.

4- Turn off the power supply, disconnect the second rheostat from the circuit and adjust the firs one to 100 Ω. Then set-up the following hardware configuration.

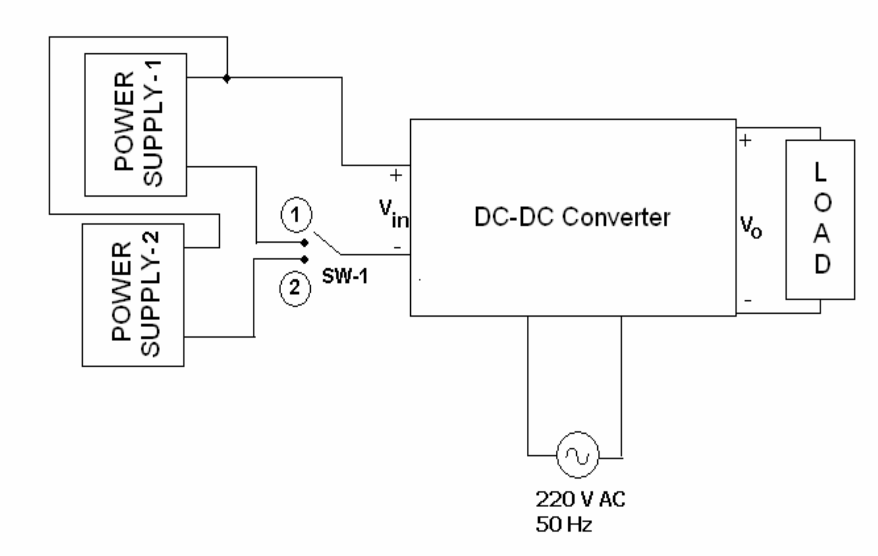

Figure 102 Converter hardware set-up (closed-loop) for DC line regulation.

Adjust the power supply-2 to 35 V and make sure that switch SW-1 is in position 1. Turn on the two power supplies. The oscilloscope must read the output voltage. Then change the switch SW-1 to position 2. So the input voltage is suddenly changed from 30 V to 35 V. Record the output voltage during input voltage change.

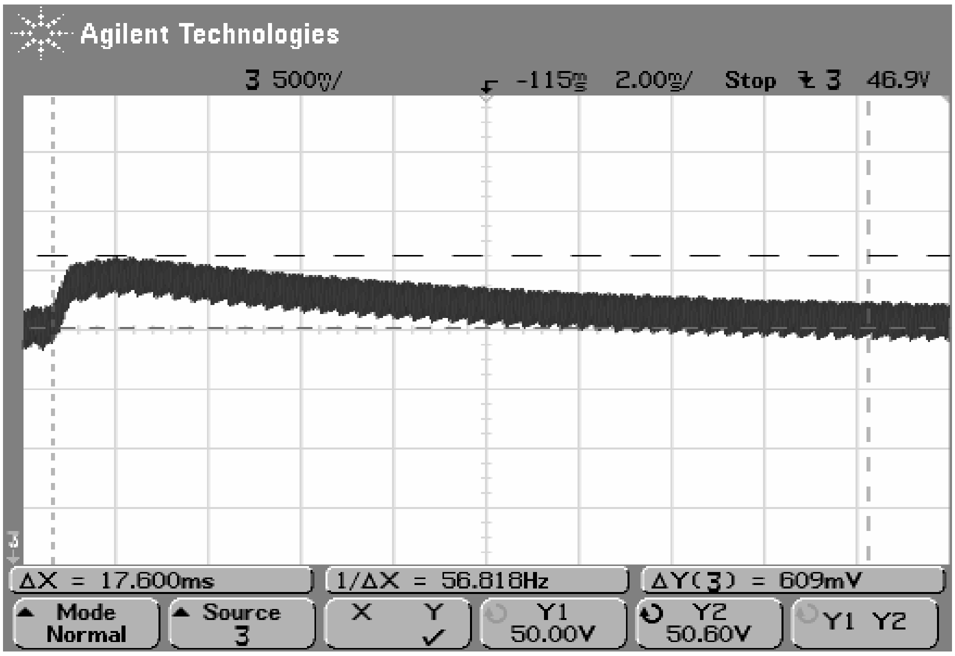

Figure 103 Load voltage characteristic for the line voltage change.

5- In the “Converter Design” tool set the following parameters.

Table 7 Closed Loop Simulation Parameters

Reference Change	Final Reference: 30 V	Change Time: 0.2 sec
Load Regulation	Final Load: 200 Ω	Change Time: 0.2 s
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.2 s
Line Regulation (AC)	Amplitude: 2.3 V peak ; Frequency: 50 Hz	Change Time: 0.1 s

Then press the “closed loop simulation” button. After simulation finish observe the dynamic behaviour of the boost converter against AC input voltage change.

5- Turn off the power supplies, disconnect the second power supply from the circuit. Connect the primary side of variac to 220 V AC and by using oscilloscope adjust the variac secondary voltage to 4.6 V AC. Turn off the varic and then set-up the following hardware configuration.

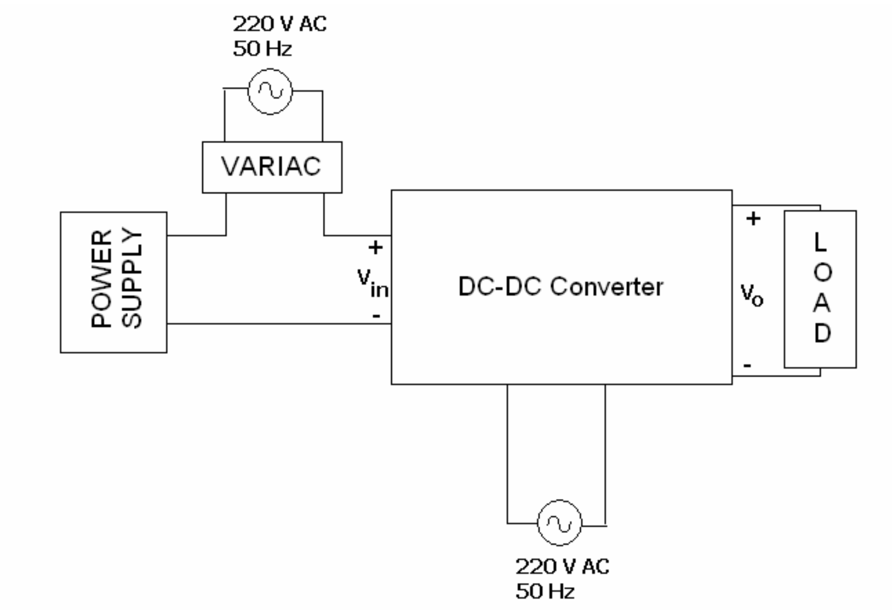

Figure 104 Converter hardware set-up (closed-loop) for AC line regulation.

Turn on the variac and then power supply. The oscilloscope must read the output voltage. In this configuration the input voltage of the conveter becomes 30 V DC + 4.6 V AC. This setup is to model the AC variations in the line voltage. Record the output voltage. Turn off the variac, power supply and the converter test box.

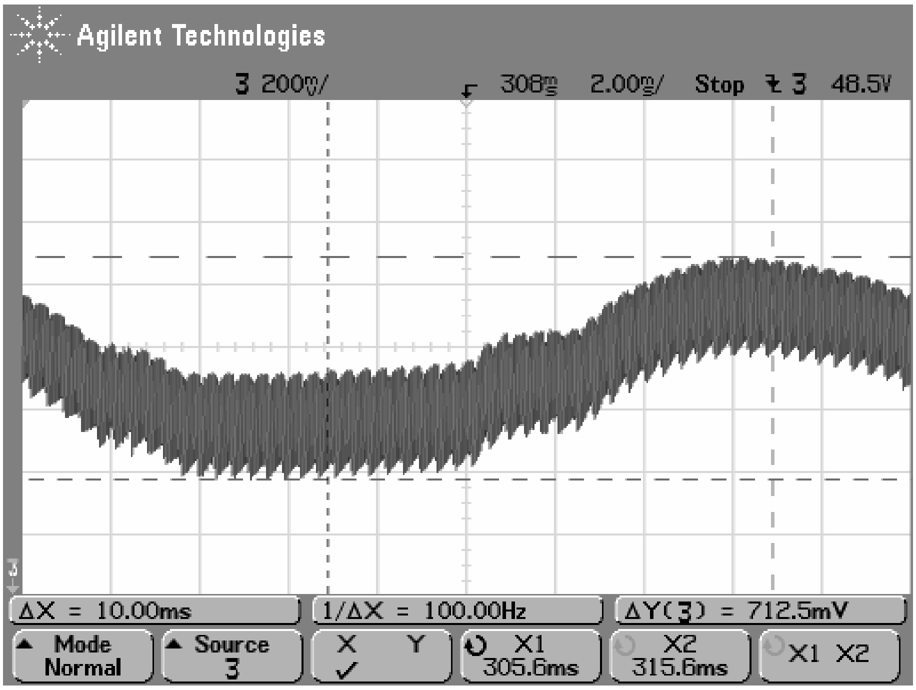

Figure 105 Boost converter load characteristics at AC line change (4.6 V peak-to-peak AC is added to the DC line input 30 V).

7.5.2.2 Study Questions

1- Discuss the difference between open and closed loop control.

2- Perform closed-loop simulations for five different k_p and k_i controller parameters and observe the converter output voltage during the same load and line changes given previously. Explain the controller effect on output voltage duing line and load changes.

3- Is PI controller is sufficient for boost converter closed-loop control? Propose another more efficient controller, explain the resons?

CHAPTER 8

CONCLUSIONS

In this thesis a boost converter is developed. First a steady-state analysis is performed. The results obtained are used only for stable operating condition. For the modeling of dynamic behaviour of the converters, small-signal analysis is used. Then, proportional-integral (PI) controller is used as control approach.

After converter is modeled and its controller parameters are derived MATLAB-Simulink is used to simulate the results. From these results it is seen that the model of converter and controller is developed suitably.

Converter design analysis is very complex from start to end which contains a lot of equations to be determined. To make this analysis easier (this means to prevent the user from the complexity of the analysis), a graphical user interface (GUI) prepared in MATLAB is used in this thesis. It is a very simple GUI to use and also provides MATLAB helpful graphics during the design. These MATLAB graphics (time response plots, simulation scopes, frequency response plots etc.) are useful to determine if the design is going well or not, comparison of the results and if there occurs a non-desired condition, to return to the start or to the required design step again. If GUI was not used, a lot of manual calculations would be needed which would yield to mistakes in design outputs. For automation of converter design, GUI is the crucial part of the thesis.

The manufactured converter has a lot of regulation options which can be adjusted during operation. Regulation options are duty-cycle regulation, reference voltage regulation, frequency regulation, input voltage regulation and load regulation. All of them are needed to observe the performance of a DC-DC converter. Only, PI compensator parameters are constant in the converter circuitry. It is known that the output voltage response time, steady-state error, overshoot transient and stability are also depend on the selected compensator. But in this thesis, a constant compensator is designed for an pre-determined operating point and applied in the manufactured converter.

It has been observed that the simulation and measurement results are very close. But there are some differences as expected: in the simulation, switches and other components are modeled nearly ideal but in fact they are not, so there are some voltage drops and some parasitic effects. On the whole, the developed setup is very useful for the power electronics laboratory because the user can see and compare the theoretical results and the practical results.

The next work may be improvement of the GUI with new control methods and adding opportunity of make comparison between the results of these different control methodologies. The other work may be adding communication capability to the "Converter Design" GUI with a computer which will provide users to view converter signal on computer screen and to adjust the compensator parameters during operation.

REFERENCES

[1] Aug 2006, Wikipedia, DC to DC Converter, http://en.wikipedia.org/wiki/DC_to_DC_converter

[2] Aug 2006, Altera, Power Supply Regulation, http://www.altera.com/support/devices/power/regulators/pow-regulators.html

[3] Aug 2006, Wikipedia, Voltage Regulator, http://en.wikipedia.org/wiki/Voltage_regulator

[4] Aug 2006, Answers, Voltage Regulator, http://www.answers.com/topic/voltage-regulator

[5] Dallas Semiconductor, APP 2031: Oct 19, 2000, http://www.maxim-ic.com/appnotes.cfm/appnote_number/2031/

[6] July-2002, SMPSRM/D Rev 3A, SWITCHMODE Power Supply Reference Manual, ON Semiconductor, http://home.eunet.cz/rysanek/pdf/mot-sw.pdf

[7] R. W. Erickson and D. Maksimovic, University of Colorado, Fundamental of Power Electronics-Second Edition,

[8] 1994-2006 The MathWorks, Inc, MATLAB Tool, Documentation>Graphical User Interfaces http://www.mathworks.com/access/helpdesk/help/techdoc/creating_guis/creating_guis.html

[9] Sept 2006, Wikipedia, Phase Margin, http://en.wikipedia.org/wiki/Phase_margin

[10] International Rectifier, IRF 530 datasheet, PD-9.3070

[11] 2000, IXYS DSS16-01A Power Schottky Rectifier Datasheet

[12] K. De Gussem´e, D.M. Van de Sype, A.P. Van den Bossche, and J.A. Melkebeek, "Input current distortion of ccm boost pfc converters operated in dcm," Proc. of the IEEE Power Electr. Spec. Conf., PESC 2003, June 15–19, 2003, Acapulco, Mexico, pp. 1685–1690.