

DESIGN OF BUCK CONVERTER FOR EDUCATIONAL TEST BENCH

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ÜMİT ERDEM KILIÇ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRICAL-ELECTRONICS ENGINEERING

DECEMBER 2006

Approval of the Graduate School of Natural and Applied Sciences of Middle East
Technical University

Prof. Dr. Canan Özgen
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of
Master of Science.

Prof. Dr. İsmet Erkmen
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully
adequate, in scope and quality, as a thesis for the degree of Master of Science.

Asst. Prof. Dr. Ahmet M. Hava
Co-Supervisor

Prof. Dr. Yıldırım Üçtuğ
Supervisor

Examining Committee Members

Prof. Dr. Muammer Ermiş (METU, EE) _____

Prof. Dr. Yıldırım Üçtuğ (METU, EE) _____

Prof. Dr. Aydın Ersak (METU, EE) _____

Asst. Prof. Dr. Ahmet M. Hava (METU, EE) _____

Prof. Dr. Işık Çadircı (HACETTEPE Univ., EE) _____

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Ümit Erdem Kılıç

Signature :

ABSTRACT

DESIGN OF BUCK CONVERTER FOR EDUCATIONAL TEST BENCH

Kılıç, Ümit Erdem

M.S., Department of Electrical and Electronics Engineering

Supervisor : Prof. Dr. Yıldırım Üçtuğ

Co-Supervisor: Asst. Prof. Dr. Ahmet M. Hava

December 2006, 141 pages

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

Keywords: Buck Converter, Small-Signal Analysis, MATLAB, GUI.

ÖZ

EĞİTİM AMAÇLI İNDİRİCİ DÖNÜŞTÜRÜCÜ TASARIMI

Kılıç, Ümit Erdem

Yüksek Lisans, Elektrik-Elektronik Mühendisliği Bölümü

Tez Yöneticisi : Prof. Dr. Yıldırım Üçtuğ

Ortak Tez Yöneticisi: Yard. Doç. Dr. Ahmet M. Hava

Aralık 2006, 141 sayfa

Bu tezde güç elektroniği ders laboratuvarlarında kullanılmak üzere indirici dönüştürücü devresi geliştirilmiştir. Bu amaçla ilk olarak indirici dönüştürücü devresinin sabit durum ve küçük işaret analizleri gerçekleştirilmiş, sonrasında devrenin açık ve kapalı çevrim kontrolleri geliştirilmiş ve simüle edilmiştir. Bu doğrultuda devre üretilmiş ve test edilmiştir. Test ve simülasyon sonuçları karşılaştırılmıştır. Son olarak, geliştirilen indirici dönüştürücü devresi ile öğrencinin laboratuvarında deney yapabilmesini sağlayacak bir deney prosedürü hazırlanmıştır.

Anahtar Kelimeler: İndirici Dönüştürücü, Küçük Sinyal Analizi, MATLAB, GUI.

TABLE OF CONTENTS

PLAGIARISM.....	iii
ABSTRACT.....	iv
ÖZ.....	v
TABLE OF CONTENTS.....	vi
LIST OF TABLE.....	ix
LIST OF FIGURE.....	x
CHAPTER	
1. DC-DC CONVERTERS.....	1
1.1 Overview.....	1
1.2 Switching Regulators	2
1.3 Switching Regulator (Converter) Types.....	3
1.3.1 Buck Converter.....	3
1.3.1.1 Continuous Mode.....	4
1.3.1.2 Discontinuous Mode.....	7
1.3.1.3 Limit Between Continuous and Discontinuous Modes.....	11
2. SMALL RIPPLE (SIGNAL) APPROXIMATION	14
2.1 Overview.....	14
2.2 Neglecting the Switching Ripple.....	15
2.3 Averaging to Remove Switching Ripple.....	17
2.4 Construction of Small Signal Equivalent Circuit Model	18
2.5 Summary of Key Points	19

2.6 Converters Transfer Functions	20
3. CONTROLLER DESIGN.....	23
3.1 Converter Controller Model-Closed Loop Control.....	23
3.2 Stability Criteria.....	29
3.2.1 Phase Margin Test.....	30
3.3 Compensator Design.....	31
4. MATLAB GRAPHICAL USER INTERFACE (GUI).....	33
4.1 Overview.....	33
4.2 “Converter Design” GUI.....	34
5. HARDWARE DESCRIPTION	40
5.1 Buck Converter Test Box and Converter Circuitry.....	40
6. SIMULATION AND EXPERIMENTAL RESULTS.....	45
7. EXPERIMENTAL PROCEDURE.....	100
7.1 Object of the Experiment.....	100
7.2 Theory of Operation.....	100
7.3 Components of the Experiment System.....	105
7.3.1 “Converter Design” GUI.....	105
7.3.2 Specification of the Buck Converter.....	110
7.4 Apparatus.....	116
7.5 Experimental Procedure.....	117
7.5.1 Open Loop Characteristics.....	117
7.5.1.1 Procedure.....	117
7.5.1.2 Study Questions.....	130

7.5.2 Closed Loop Characteristics.....	130
7.5.2.1 Procedure.....	130
7.5.2.2 Study Questions.....	136
8. CONCLUSION.....	137
REFERENCES.....	140

LIST OF TABLES

TABLES

Table 1 Salient features of the small-signal transfer function of buck converter [9].	22
Table 2 Buck converter test box specification	41
Table 3 Closed loop simulation parameters (reference change)	91
Table 4 Closed loop simulation parameters (load change)	93
Table 5 Closed loop simulation parameters (DC line change)	95
Table 6 Closed loop simulation parameters (AC line change)	97
Table 7 Buck converter test box specification	111
Table 8 Buck converter part list	115
Table 9 Apparatus used in experiment	117
Table 10 Closed Loop Simulation Parameters	130
Table 11 Closed Loop Simulation Parameters	132
Table 12 Closed Loop Simulation Parameters	134

LIST OF FIGURES

FIGURES

Figure 1 Buck converter [5].	4
Figure 2 Voltage and current waveforms for a buck converter in on and off state [6].	5
Figure 3 Inductor current of a buck converter in continuous conduction mode.	7
Figure 4 Inductor current of a buck converter in boundary condition.	8
Figure 5 Inductor current of a buck converter in discontinuous conduction mode.	9
Figure 6 Variations in switch gate drive signal and converter output voltage.	15
Figure 7 Frequency spectrum of output voltage [9].	16
Figure 8 Nonlinear static control-to-output characteristic of a buck converter [9].	18
Figure 9 Complete equivalent circuit for a buck converter [9].	19
Figure 10 Output voltage depends on duty cycle, input voltage, and load current [9].	23
Figure 11 General control scheme of a converter [9].	24
Figure 12 AC equivalent scheme of a converter controller [9].	25
Figure 13 Characteristics of the gain “T” and “T/(1 + T)” at different frequencies [9].	28
Figure 14 “Converter Design” GUI	34
Figure 15 General view of the DC-DC converter test box.	40
Figure 16 Hardware overview.	41
Figure 17 “IR2125” Current sensing circuit configuration.	43

Figure 18 Simulation result - Buck converter output voltage (oscilloscope channel is at DC mode)..... 46

Figure 19 Measurement result-Buck converter output voltage (oscilloscope channel is at DC mode). 47

Figure 20 Simulation result-Buck converter output voltage (oscilloscope channel is at AC mode). 48

Figure 21 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode). 48

Figure 22 Simulation result-Buck converter diode voltage. 49

Figure 23 Measurement result-Buck converter diode voltage. 50

Figure 24 Simulation result-Buck converter inductor current. 51

Figure 25 Measurement result-Buck converter inductor current. 51

Figure 26 Simulation result-Buck converter input current. 52

Figure 27 Measurement result-Buck converter input current. 52

Figure 28 Simulation result-Buck converter switch voltage..... 53

Figure 29 Measurement result-Buck converter switch voltage..... 54

Figure 30 Simulation result-Buck converter inductor voltage..... 55

Figure 31 Measurement result-Buck converter inductor voltage..... 55

Figure 32 Simulation result-Buck converter output voltage (oscilloscope channel is at DC mode)..... 57

Figure 33 Measurement result-Buck converter output voltage..... 58

Figure 34 Simulation result-Buck converter output voltage (oscilloscope channel is at AC mode)..... 59

Figure 35 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).	59
Figure 36 Simulation result-Buck converter diode voltage.	60
Figure 37 Measurement result-Buck converter diode voltage.	61
Figure 38 Parasitic network causing oscillations [13]	62
Figure 39 Simulation result-Buck converter inductor current.	63
Figure 40 Measurement result-Buck converter inductor current.	64
Figure 41 Simulation result-Buck converter input current.	65
Figure 42 Measurement result-Buck converter input current.	65
Figure 43 Simulation result-Buck converter switch voltage.	66
Figure 44 Measurement result-Buck converter switch voltage.	67
Figure 45 Simulation result-Buck converter inductor voltage.	68
Figure 46 Measurement result-Buck converter inductor voltage.	68
Figure 47 Simulation result-Buck converter output voltage (oscilloscope channel is at DC mode).	70
Figure 48 Measurement result-Buck converter output voltage (oscilloscope channel is at DC mode).	70
Figure 49 Simulation result-Buck converter output voltage (oscilloscope channel is at AC mode).	71
Figure 50 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).	71
Figure 51 Simulation result-Buck converter diode voltage.	72
Figure 52 Measurement result-Buck converter diode voltage.	73

Figure 53 Simulation result-Buck converter inductor current.	74
Figure 54 Measurement result-Buck converter inductor current.	74
Figure 55 Simulation result-Buck converter input current.	75
Figure 56 Measurement result-Buck converter input current.	76
Figure 57 Simulation result-Buck converter switch voltage.....	77
Figure 58 Measurement result-Buck converter switch voltage.....	77
Figure 59 Simulation result-Buck converter inductor voltage.....	78
Figure 60 Measurement result-Buck converter inductor voltage.....	79
Figure 61 Frequency response of “Small-Signal Model (G_{vd})”.....	81
Figure 62 Poles and zeroes of “Small-Signal Model (G_{vd})”.....	82
Figure 63 Frequency Response of “Uncompensated Loop (T_u)”.....	83
Figure 64 Poles and zeroes of “Uncompensated Loop (T_u)”.....	84
Figure 65 PI compensator frequency response.	86
Figure 66 Closed loop (reference-to-output) transfer function time response.	87
Figure 67 Frequency Response of “Compensated Loop (T)”.....	88
Figure 68 Poles and Zeroes of “Compensated Loop (T)”.....	89
Figure 69 “Frequency Response Design Summary” at the end of design.	90
Figure 70 Simlation result-Buck converter output voltage at reference change (at t = 0 s, reference is setting from 0 V to 15 V and at t = 0.03 s, reference is setting from 15 V to 0 V).	91
Figure 71 Measurement result-Buck converter output voltage at reference change (at t = 0.03 s, reference is setting from 0 V to 15 V).....	92

Figure 72 Measurement result-Buck converter output voltage at reference change (at $t = 0.03$ s, reference is setting from 15 V to 0 V).....	92
Figure 73 Simulation result-Buck converter load characteristics at load change (at $t = 0.03$ s, load is changed from 7Ω to 25Ω).	94
Figure 74 Measurement result-Buck converter output voltage at load change (at $t = 0.03$ s, load is changing from 7Ω to 25Ω).	94
Figure 75 Simulation result-Buck converter load characteristics at DC line change (at $t = 0.03$ s, 5 V DC is added to the DC line input 30 V).	96
Figure 76 Measurement result-Buck converter load characteristics at DC line change (at $t = 0.03$ s, 5 V DC is added to the DC line input 30 V).	96
Figure 77 Simulation result-Buck converter load characteristics at AC line change (at $t = 0.03$ s, 4.6 V peak AC is added to the DC line input 30 V).	98
Figure 78 Measurement result-Buck converter output voltage at 4.6 V peak-to-peak AC line change (oscilloscope at AC Mode).	98
Figure 79 Buck converter.....	101
Figure 80 Inductor current of a buck converter in boundary condition.	102
Figure 81 Parasitic network causing oscillations.	104
Figure 82 “”Converter Design” GUI.....	106
Figure 83 General view of the DC-DC converter test box.....	110
Figure 84 Hardware overview.....	112
Figure 85 Circuit layout.	113
Figure 86 Converter hardware set-up (open-loop).....	118

Figure 87 Measurement result-Buck converter output voltage (oscilloscope channel is at DC mode).	119
Figure 88 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).	119
Figure 89 Measurement result-Buck converter diode voltage.	120
Figure 90 Measurement result-Buck converter inductor current.	120
Figure 91 Measurement result-Buck converter input current.	121
Figure 92 Measurement result-Buck converter switch voltage.....	121
Figure 93 Measurement result-Buck converter inductor voltage.....	122
Figure 94 Measurement result-Buck converter output voltage (oscilloscope channel is at DC mode).	122
Figure 95 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).	123
Figure 96 Measurement result-Buck converter diode voltage.	123
Figure 97 Measurement result-Buck converter inductor current.	124
Figure 98 Measurement result-Buck converter input current.	124
Figure 99 Measurement result-Buck converter switch voltage.....	125
Figure 100 Measurement result-Buck converter inductor voltage.....	125
Figure 101 Measurement result-Buck converter output voltage.....	126
Figure 102 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).	127
Figure 103 Measurement result-Buck converter diode voltage.	127
Figure 104 Measurement result-Buck converter inductor current.	128

Figure 105 Measurement result-Buck converter input current.	128
Figure 106 Measurement result-Buck converter switch voltage.....	129
Figure 107 Measurement result-Buck converter inductor voltage.....	129
Figure 108 Converter hardware set-up (closed-loop) for load regulation.....	131
Figure 109 Output voltage characteristic during load change.	132
Figure 110 Converter hardware set-up (closed-loop) for DC line regulation.....	133
Figure 111 Measurement result-Buck converter load characteristics at DC line change (at $t = 0.03$ s, 5 V DC is added to the DC line input 30 V).....	134
Figure 112 Converter hardware set-up (closed-loop) for AC line regulation.....	135
Figure 113 Measurement result-Buck converter output voltage at 4.6 V peak-to-peak AC line change (oscilloscope at AC Mode).....	136

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) [1]. 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].

DC-DC voltage regulators (converters) are also 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
- Ability to step-down or step-up output voltages, or both
- DC-DC converter efficiency ($POUT / PIN$)
- Output voltage ripple
- Output load transient response

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” in order to obtain a desired voltage. This method is basically different from linear regulation by its smaller power consumption [3].

1.2 Switching Regulators

Instead of controlling a variable resistance as in linear regulators, 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].

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 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 [2].

The clear advantage of switching regulators is efficiency, as minimal power is dissipated in the power path (switches) when the output supply voltage is sufficient for the load state. The disadvantage of switching regulators is complexity, as several

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].

1.3 Switching Regulator (Converter) Types

The various topologies of the 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

In this thesis, “Buck” converter is investigated among the others.

1.3.1 Buck Converter

Buck converter is a high efficiency step-down DCDC switching converter. It is one of the most fundamental topologies of any switching power supply configuration. Buck, or step-down, voltage converters produce an average output voltage lower than the input source voltage [2]. They can convert a voltage source (typically 8 V to 25 V) into a lower regulated voltage (typically 0.5 V to 9 V). Figure 1 shows a basic buck topology using ideal components. Stepdown converters transfer small packets of energy using a switch, a diode, an inductor and several capacitors [7]. The

inductor serves as a current source to the output load impedance. The converter uses a switch, typically a MOSFET, to pulse width modulate the voltage into an inductor. When the switch is on, the inductor current increases, inducing a positive voltage drop across the inductor and a lower output supply voltage in reference to the input source voltage [2]. When the switch is off, the inductor current discharges, inducing a negative voltage drop across the inductor [2]. Because one port of the inductor is tied to ground, the other port will have a higher voltage level, which is the target output supply voltage [2]. The output capacitance acts as a low-pass filter, reducing output voltage ripple as a result of the fluctuating current through the inductor [2]. The diode provides a current path for the inductor when the switch is off [2]. A general view of the converter is given in Figure 1.

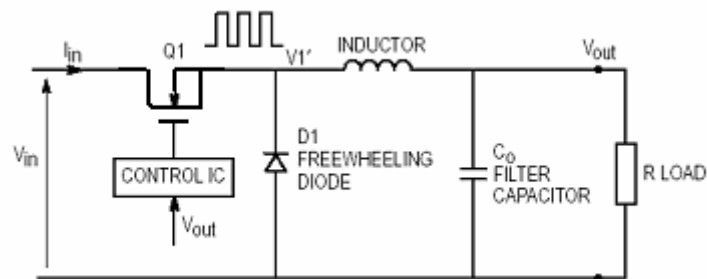


Figure 1 Buck converter [5].

1.3.1.1 Continuous Mode

A Buck converter operates in continuous conduction mode (CCM) if the current through the inductor (I_L) never falls to zero during the commutation cycle [8]. In this mode, the current and voltage waveforms and the two operating regions can be given as in Figure 2.

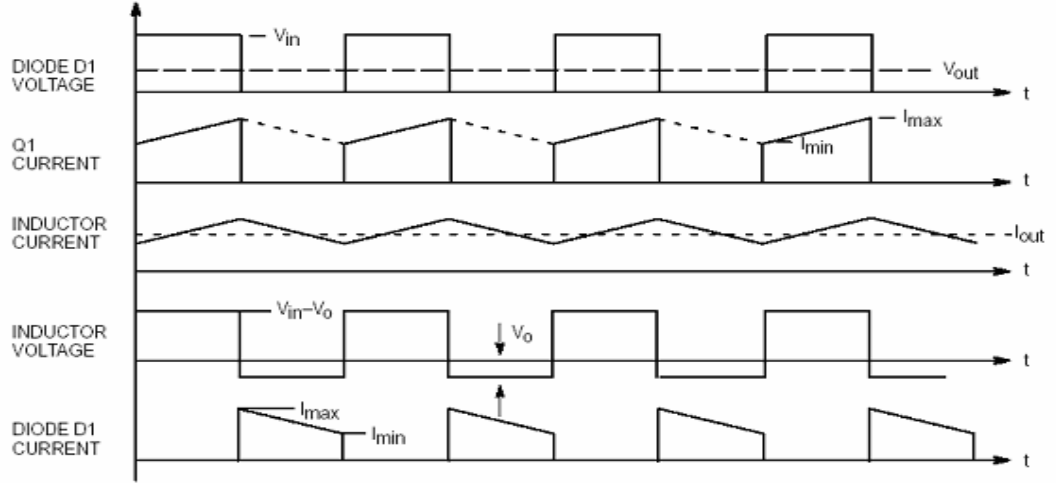


Figure 2 Voltage and current waveforms for a buck converter in on and off state [6].

When the switch above is closed (on-state) the voltage across the inductor is equal to $V_{in} - V_o$ [8]. The current through the inductor rises linearly [8]. As the diode is reverse-biased by the voltage source, no current flows through it [8]. When the switch is opened (off state), the diode is forward biased [8]. The voltage across the inductor is equal to $-V_o$ (neglecting diode drop) [8]. The current I_L decreases [8]. It can be seen that the energy stored in L increases during on-time (as I_L increases) and then decreases during the off-state [8]. L is used to transfer energy from the input to the output of the converter [8]. The rate of change of the I_L is given by [8]:

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

with V_L equal to $(V_{in} - V_o)$ during the on-state and to $(-V_o)$ during the off-state [8]. Therefore, the increase in current during the on-state is given by [8]:

$$\Delta I_{Lon} = \int_0^{t_{on}} dI_L = \int_0^{t_{on}} \frac{V_L}{L} dt = \frac{(V_i - V_o) \cdot t_{on}}{L}$$

Identically, the decrease in current during the off-state is given by [8]:

$$\Delta I_{Lon} = \int_0^{t_{off}} dI_L = \int_0^{t_{off}} \frac{V_L}{L} dt = -\frac{V_o \cdot t_{off}}{L}$$

If it is assumed that the converter operates in steady state [8], the energy stored in each component at the end of a commutation cycle T is equal to that at the beginning of the cycle [8]. That means that the current I_L is the same at $t = 0$ and at $t = T$ [8]. Therefore,

$$\Delta I_{Lon} + \Delta I_{Loff} = 0$$

So, from the equations above [8]:

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

It is known that [8]:

$$t_{on} = D \cdot T \quad \text{and} \quad t_{off} = T - D \cdot T$$

where D is a scalar called the duty cycle with a value between 0 and 1 [8]. This yields [8]:

$$(V_i - V_o) \cdot D \cdot T - V_o \cdot (T - D \cdot T) = 0$$

This equation can be rewritten as [8]:

$$V_o = D \cdot V_i$$

From this equation, it can be seen that the output voltage of the converter varies linearly with the duty cycle for a given input voltage [8]. As the duty cycle D is equal to the ratio between t_{on} and the period T , it cannot be more than 1 ($V_o \leq V_i$) [8]. This is why this converter is referred to as a step-down converter [8].

1.3.1.2 Discontinuous Mode

In some cases, the amount of energy required by the load is small enough to be transferred in a time lower than the whole commutation period [8]. In this case, the current through the inductor falls to zero during part of the period [8].

Now, it is considered how the inductor current waveform changes as the load power is reduced. The inductor current Δi_L waveform is sketched in Figure 3 for continuous conduction mode of Buck converter. The inductor current waveform contains a dc component I , plus a switching ripple of peak amplitude Δi_L . The inductor current dc component I is equal to the load current I_o ($I_o = V_o/R$).

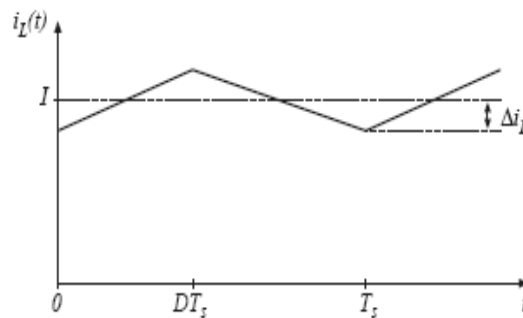


Figure 3 Inductor current of a buck converter in continuous conduction mode.

The switching ripple peak amplitude is equal to:

$$\Delta i_L = \frac{(V_i - V_o)}{2L} DT_s = \frac{V_i DD'T_s}{2L}$$

The ripple magnitude depends on the applied voltage ($V_i - V_o$), on the inductance L , and on the transistor conduction time DT_s . But it does not depend on the load resistance R .

Now if it is supposed that the load resistance R is increased, the dc load current is decreased. The dc component of inductor current I will then decrease, but the ripple magnitude Δi_L will remain unchanged. If R is further increased, eventually the boundary point is reached where $I = \Delta i_L$, as illustrated in Figure 4. It can be seen that the inductor current $i_L(t)$ is zero at the end of the switching period. Yet the load current is positive and nonzero.

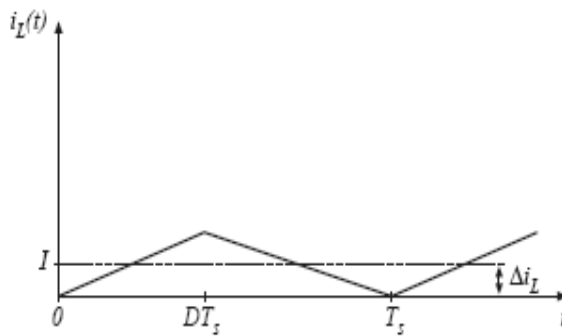


Figure 4 Inductor current of a buck converter in boundary condition.

If the load resistance is still increased, the diode current cannot be negative; therefore, the diode must become reverse biased before the end of the switching period. As illustrated in Figure 5, there are now three subintervals during each switching period T_s . During the first subinterval of length $D_1 T_s$, the transistor conducts, and the diode conducts during the second subinterval of length $D_2 T_s$. At the end of the second subinterval the diode current reaches zero, and for the

remainder of the switching period neither the transistor nor diode conduct. The converter operates in the discontinuous conduction mode.

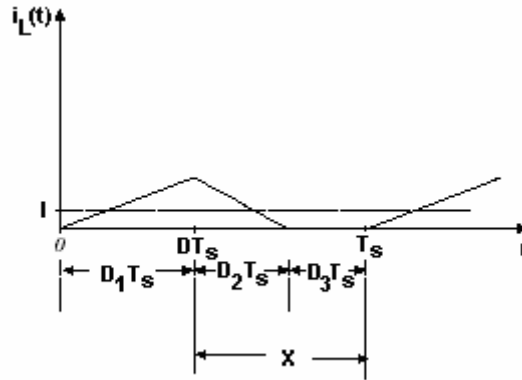


Figure 5 Inductor current of a buck converter in discontinuous conduction mode.

The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle [8]. This has, however, some effect on the previous equations [8].

Consider that the converter still operates in steady state [8]. Therefore, the energy in the inductor is the same at the beginning and at the end of the cycle (in the case of discontinuous mode, it is zero) [8]. This means that the average value of the inductor voltage (V_L) is zero [8]. This yield:

$$(V_i - V_o) \cdot D \cdot T - V_o \cdot x \cdot T = 0$$

So the value of x is [8]:

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

The output current delivered to the load (I_o) is constant; since the output capacitor is large enough to maintain a constant voltage across its terminals during a commutation cycle [8]. This implies that the current flowing through the capacitor has a zero average value [8]. Therefore,

$$I_{Lavg} = I_o$$

where I_{Lavg} is the average value of the inductor current [8]. The inductor current waveform has a triangular shape [8]. Therefore, the average value of I_L can be sorted out geometrically as follows [8]:

$$I_{Lavg} = \left(\frac{1}{2} I_{Lmax} \cdot D \cdot T + \frac{1}{2} I_{Lmax} \cdot x \cdot T \right) \frac{1}{T} = \frac{I_{Lmax} (D + x)}{2} = I_o$$

The inductor current is zero at the beginning and rises during t_{on} up to I_{Lmax} [8]. I_{Lmax} is equal to [8]:

$$I_{Lmax} = \frac{V_i - V_o}{L} D \cdot T$$

Substituting the value of I_{Lmax} in the previous equation leads to [8]:

$$I_o = \frac{(V_i - V_o) D \cdot T (D + x)}{2L}$$

and substituting & by the expression given above yields [8]:

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

This latter expression can be written as [8]:

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

It can be seen that the output voltage of a buck converter operating in discontinuous conduction mode (DCM) is much more complicated than its counterpart of the continuous conduction mode (CCM) [8]. Furthermore, the output voltage is now a function not only of the input voltage (V_i) and the duty cycle D , but also of the inductance value (L), the commutation period (T) and the output current (I_o) [8].

1.3.1.3 Limit Between Continuous and Discontinuous Modes

As mentioned at the beginning of this section, the converter operates in discontinuous mode when low current is drawn by the load, and in continuous mode at higher load current levels [8]. The limit between discontinuous and continuous modes is reached when the inductor current falls to zero exactly at the end of the commutation cycle [8].

Inductor current ripple is equal to:

$$\Delta i_L = \frac{(V_i - V_o)}{2L} DT_s = \frac{V_i DD' T_s}{2L}$$

In continuous conduction mode, the diode current is positive over the entire interval $DT_s < t < T_s$ provided that $I > \Delta i_L$. (I is the dc component of inductor current). Hence, the conditions for operation in the continuous and discontinuous conduction modes are:

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

where I and Δi_L are found assuming that the converter operates in the continuous mode. During the first subinterval, the inductor current supplies the load current and the capacitor is partially charged. During the second subinterval, the capacitor

current supplies the load current and the capacitor is partially discharged. The net change in capacitor charge over one switching period is equal to zero and can be found by integrating the $i_c(t)$ waveform:

$$\int i_c = \left(I - \frac{V_o}{R}\right)DT_s + \left(\frac{V_o}{R} - I\right)D'T_s = 0$$

Simplification is applied and I is found as:

$$I = \frac{V_o}{R}$$

By inserting buck converter expressions for I and Δi_L comparison, the following expression is obtained:

$$\frac{DV_s}{R} < \frac{DD'T_s V_i}{2L}$$

Simplification leads to:

$$\frac{2L}{RT_s} < D'$$

This can be also expressed as:

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

$$K = \frac{2L}{RT_s} \quad \text{and} \quad K_{crit}(D) = D'$$

The dimensionless parameter K is a measure of tendency of a converter to operate in the discontinuous conduction mode. Large value of K leads to continuous mode operation, while small values leads to the discontinuous mode for some values of

duty cycle. The critical value of K at the boundary between modes, $K_{crit}(D)$, is a function of duty cycle, and is equal to D' for the buck converter.

The next section is related with the small ripple approximation and control of a buck converter, formula and derived equivalent circuitry needed for controller design.

CHAPTER 2

SMALL RIPPLE (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.

While modeling the converter in steady-state region, it is assumed that there is no change in the input voltage and load [9]. 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 [9]. But, when controlling a converter, there are always some disturbances which generate uncertainties [9]. 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 converter controller design with small-signal analysis will be given later).

Essentially, the question “How do ac variations in $v_g(t)$, R , or $d(t)$ affect the output voltage $v(t)$?” is the starting point of the small-signal analysis need and has importance for exact dynamic modeling. 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 buck converter small-signal modeling.

2.2 Neglecting the Switching Ripple

Suppose the duty cycle is modulated sinusoidally. So duty cycle expression is given as [9]:

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

where D and D_m are constants, $|D_m| \ll D$, and the modulation frequency w_m is much smaller than the converter switching frequency w_s . Figure 6 shows the resulting variations in switch gate drive signal and converter output voltage [9].

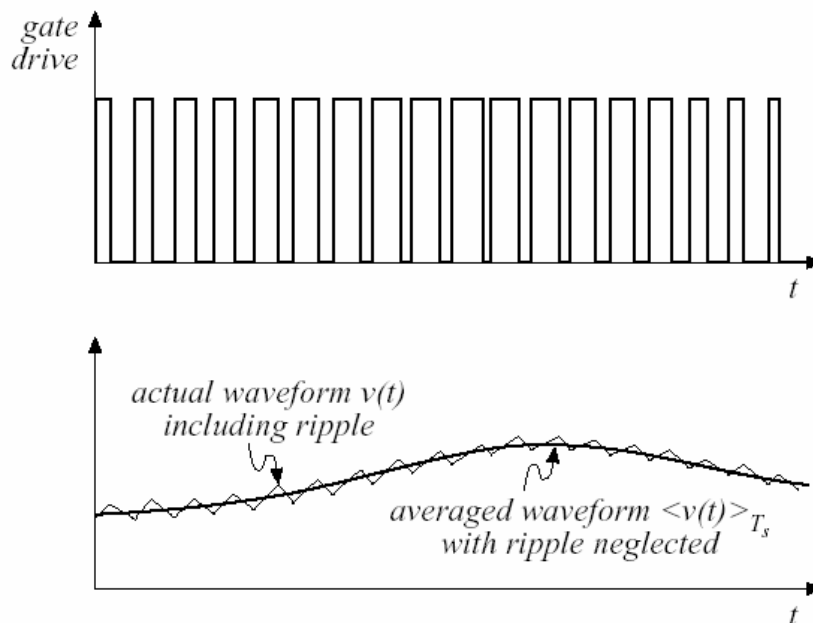


Figure 6 Variations in switch gate drive signal and converter output voltage.

In accordance with the gate driver signal (duty cycle) change, the output voltage is also changed with ripple on itself. It should be noted that the average of the ac ripple signal is equal to zero in one switching cycle [9]. 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 7 shows the frequency spectrum of output voltage. It is seen that this spectrum contains frequency components at:

- Modulation frequency and its harmonics [9]
- Switching frequency and its harmonics [9]
- Sidebands of switching frequency [9]

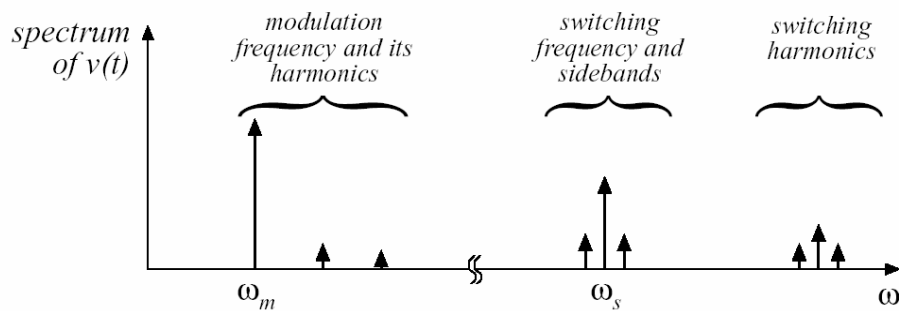


Figure 7 Frequency spectrum of output voltage [9].

Switching ripple and high-frequency components (switching harmonics and sidebands) are too small according to low frequency components. If this ripple is neglected, then only low frequency components (modulation frequency and harmonics) remain [9].

At this point, the objective of the small signal assumption in converter modeling can be given more accurately: 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 [9]. To achieve this objective, small

signal modeling ignores the switching ripple, complicated switching harmonics and sidebands [9]. The main approach is removing switching harmonics by averaging all waveforms over one switching period.

2.3 Averaging to Remove Switching Ripple

Average of a signal (named as “x”) over one switching period can be given as [9]:

$$\langle x_L(t) \rangle_{T_s} = \frac{1}{T_s} \int_t^{t+T_s} x(\tau) d\tau$$

where T_s is the period of the signal. Average of inductor current and capacitor voltage over one switching period in converter can also be given as below [9]:

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

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

It should be noted that that, in steady state, average inductor voltage and capacitor current are equal to zero [9]:

$$\langle v_L(t) \rangle_{T_s} = 0$$

$$\langle i_C(t) \rangle_{T_s} = 0$$

The averaged voltages and currents are, in general, nonlinear functions of the converter duty cycle, voltages, and currents [9]. Hence, linearizing is a must by constructing a small-signal converter model. Figure 8 shows the nonlinear static control-to-output characteristic of a buck converter [9]. 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) [9]. 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. At this point it can be clearly said that: “The small-signal model is correctly reflecting the converter in and near the DC operating point.”

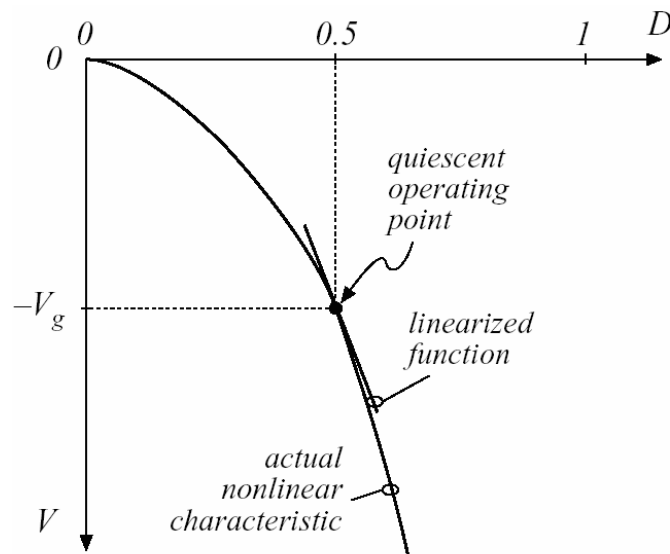


Figure 8 Nonlinear static control-to-output characteristic of a buck converter [9].

2.4 Construction of Small-Signal Equivalent Circuit Model

The linearized small-signal converter equations are as below [9]:

$$L \frac{d\hat{i}(t)}{dt} = D\hat{v}_g(t) - \hat{v}(t) + V_g \hat{d}(t)$$

$$C \frac{d\hat{v}(t)}{dt} = -\frac{\hat{v}(t)}{R} + \hat{i}(t)$$

$$\hat{i}_g(t) = D\hat{i}(t) + I\hat{d}(t)$$

The resulting equivalent circuit of a buck converter is given in Figure 9 [9].

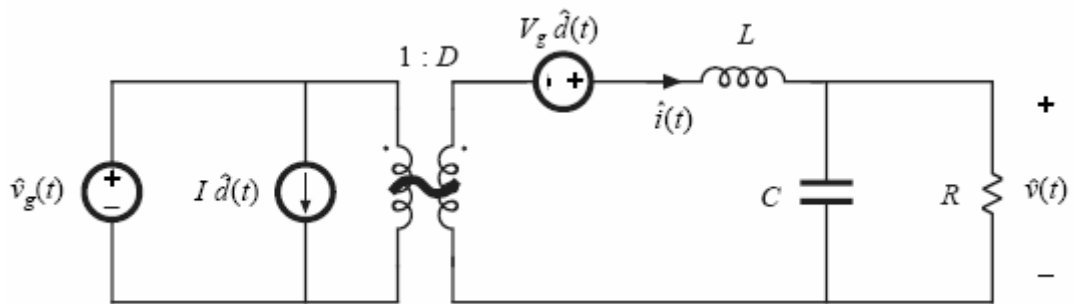


Figure 9 Complete equivalent circuit for a buck converter [9].

2.5 Summary of Key Points

Finally it will be helpful to re-mention the following key points about small signal modeling of a converter [9].

- The key step is to average the converter waveforms over one switching period. This removes the switching harmonics, thereby exposing directly the desired dc and low-frequency ac components of the waveforms. In particular, expressions for the averaged inductor voltages, capacitor currents, and converter input current are usually found [9].

- Since switching converters are nonlinear systems, it is desirable to construct small-signal linearized models. This is accomplished by perturbing and linearizing the averaged model about a quiescent operating point [9].

The next section is related with determination of the converter transfer function. To see the converter frequency response to its inputs, this transfer function is needed. Also, in controller design part, this derived transfer function will be used to determine the necessary controller parameters.

2.6 Converters 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 [9]. The converter outputs are the affected parameters while the duty cycle, input voltage, input impedance and load are the reasons of the converter outputs changes [9]. In this section, buck converter will be investigated as example.

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 $v(s)$ [9]:

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

This transfer function describes how variations or disturbances in the applied input voltage $v_g(t)$ lead to disturbances in the output voltage $v(t)$ [9]. For example, in an off-line power supply, the converter input voltage $v_g(t)$ contains undesired even harmonics of the ac power line voltage [9]. The transfer function $G_{vg}(s)$ is used to determine the effect of these harmonics on the converter output voltage $v(t)$ [9].

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 $d(s)$ [9]:

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

This transfer function describes how control input variations $d(s)$ influence the output voltage $v(s)$ [9]. 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 [9]. This quantity is also important in voltage regulator design [9].

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

The converter contains two independent ac inputs: the control input $d(s)$ and the line input $v_g(s)$ [9]. The ac output voltage variations $v(s)$ are expressed as the superposition of terms arising from these two inputs [9]:

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

where;

$$G_{vg}(s) = G_{g0} \frac{1}{1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

$$G_{vd}(s) = G_{d0} \frac{\left(1 - \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2\right)}$$

The salient features of the line-to-output and control-to-output transfer functions of a buck converter are summarized in Table 1[9].

Table 1 Salient features of the small-signal transfer function of buck converter [9]

G_{g0}	G_{d0}	ω_0	Q	ω_z
D	$\frac{V}{D}$	$\frac{V}{\sqrt{LC}}$	$R\sqrt{\frac{C}{L}}$	∞

The next chapter is related with converter controller design using the converter transfer functions derived in this section.

CHAPTER 3

CONTROLLER DESIGN

3.1 Converter Controller Model –Closed Loop Control

It is known that the output voltage of a switching converter depends on duty cycle D , input voltage v_g , and load current i_{load} (or output impedance), which can be represented as in Figure 10 [9].

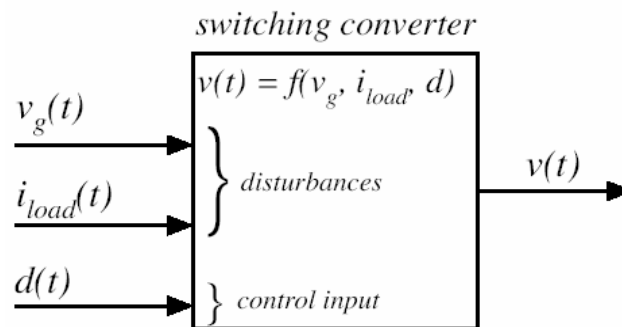


Figure 10 Output voltage depends on duty cycle, input voltage, and load current [9].

The main objective of the controller is to maintain constant output voltage $v(t) = V$, in spite of disturbances in $v_g(t)$ and $i_{load}(t)$ [9]. So, without a controller, setting the duty cycle to a single value does not mean a constant output voltage under all conditions. The main objective is to build 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 [9].

A general control scheme of a converter is given in Figure 11 [9]:

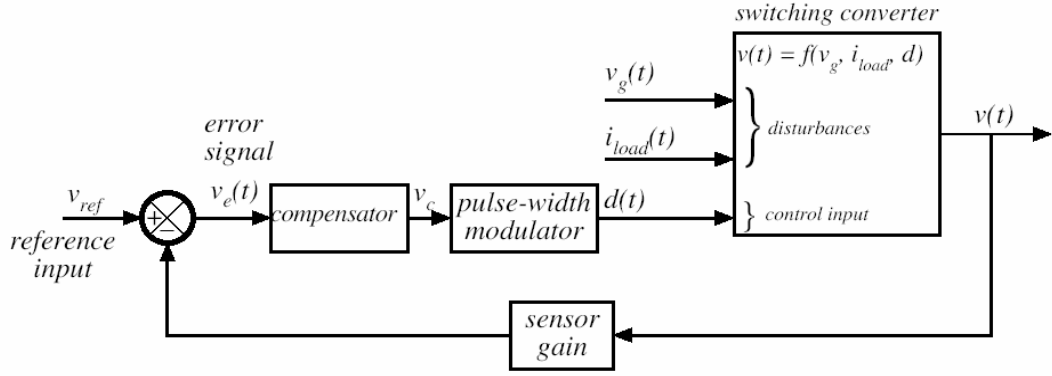


Figure 11 General control scheme of a converter [9].

The output voltage $v(t)$ is measured, using a “sensor” with gain $H(s)$. The sensor output signal is compared with a reference input voltage $v_{ref}(s)$. The objective is to make $H(s)v(s)$ equal to $v_{ref}(s)$, so that $v(s)$ accurately follows $v_{ref}(s)$ regardless of disturbances or component variations in the compensator, pulse-width modulator, gate driver, or converter power stage. Output voltage can be expressed as [9]:

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

where:

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

First off all the signal of the feedback loop is perturbed and linearized as in the small signal modeling [9]. This means, for example:

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

$$v_e(t) = V_e + \hat{v}_e(t) \quad \text{etc.}$$

It is known that the first term at the right side of the equations demonstrates the dc constants (at operating point); the second is for the ac component [9]. 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 12 [9].

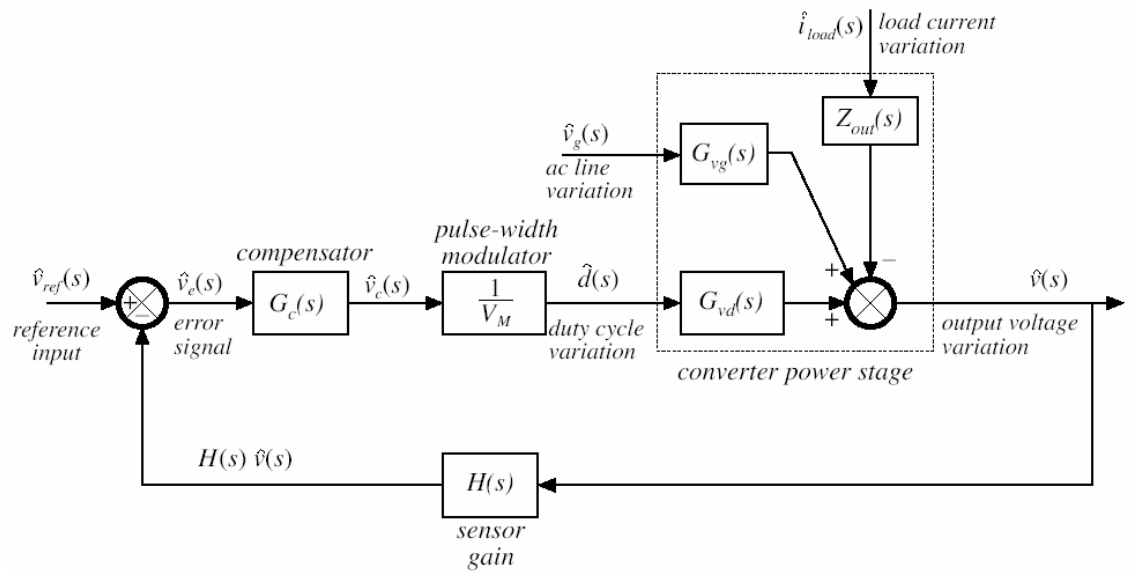


Figure 12 AC equivalent scheme of a converter controller [9].

By manipulating block diagram to solve for $v(s)$, the following is obtained [9]:

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

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,

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

Loop gain $T(s)$ is equal to the product of the gains around the negative feedback loop. Original (open-loop) line-to-output transfer function is [9]:

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

With addition of negative feedback, the line-to-output transfer function becomes [9]:

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

So, feedback reduces the line-to-output transfer function by a factor of [9]:

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

So, it is clear that, if $T(s)$ is large in magnitude, then the line-to-output transfer function becomes small [9]. This means that the ac variation on the input voltage will not affect the output, which is a desired condition in converter applications [9].

Original (open-loop) output impedance is [9]:

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

With addition of negative feedback, the output impedance becomes [9]:

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

Feedback reduces the output impedance by a factor of [9]:

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

So, it is clear that, if $T(s)$ is large in magnitude, then the output impedance is greatly reduced in magnitude [9]. This means that the load variation will not affect the output, which is a desired condition in converter applications [9].

Closed-loop transfer function from $v(s)$ to $v_{ref}(s)$ is [9]:

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

If the loop gain is large in magnitude, i.e., $\|T\| \gg 1$, then $(1+T) = T$ and $T/(1+T) = T/T = 1$. The transfer function then becomes [9]:

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

which is independent of the gains in the forward path of the loop. This result applies equally well to dc values [9]:

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

This means that when a reference signal is applied to the controller, the output of the converter will assume only the desired value which is equal to the reference signal product by sensor gain, which is a desired condition in converter applications [9].

In controller design, loop gain “T” 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.

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

$$\frac{1}{1+T(s)} \approx \begin{cases} \frac{1}{T(s)} & \text{for } \|T\| \gg 1 \\ 1 & \text{for } \|T\| \ll 1 \end{cases}$$

The following Bode diagram (Figure 13) is given only to show the characteristics of the gain “T” and “T/(1 + T)” at different frequencies [9].

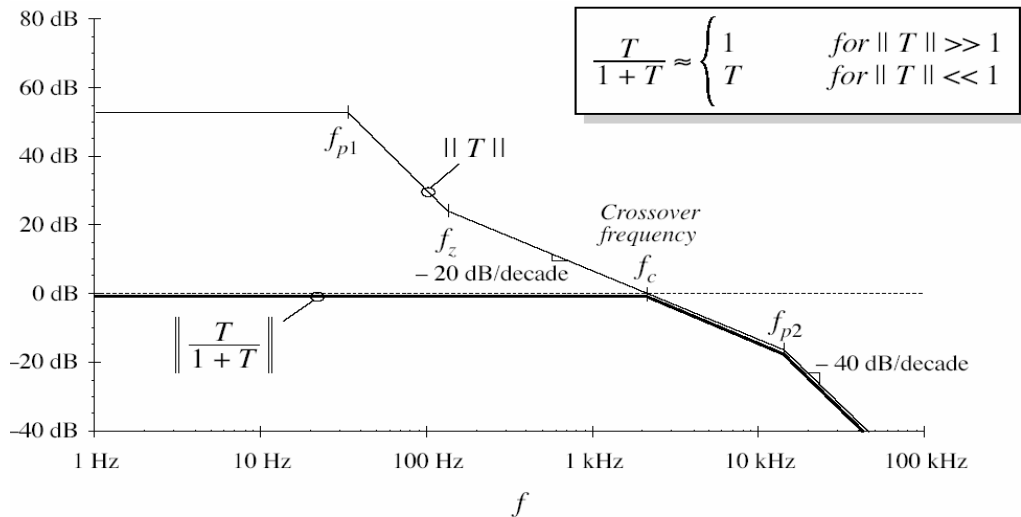


Figure 13 Characteristics of the gain “T” and “T/(1 + T)” at different frequencies [9].

At frequencies sufficiently less than the crossover frequency, the loop gain $T(s)$ has large magnitude [9]. 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 [9]. At frequencies above the crossover frequency, $\|T\| < 1$, the quantity $T/(1+T)$ then has a magnitude approximately equal to $T(s)$, and is obtained as [9]:

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

At frequencies where $\|T\| < 1$, the loop has essentially no effect on the transfer function from the reference to the output [9]. Below the crossover frequency, $f < f_c$ and $\|T\| > 1$. Then $1/(1+T) = 1/T$, and disturbances are reduced in magnitude by $1/\|T\|$. Above the crossover frequency, $f > f_c$ and $\|T\| < 1$. Then $1/(1+T) = 1$, and the feedback loop has essentially no effect on disturbances [9]. This situation can be summarized below:

$$\frac{1}{1+T(s)} \approx \begin{cases} \frac{1}{T(s)} & \text{for } \|T\| \gg 1 \\ 1 & \text{for } \|T\| \ll 1 \end{cases}$$

3.2 Stability Criteria

Original transfer functions, before introduction of feedback (“open-loop transfer functions”) are [9]:

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

Upon introduction of feedback, these transfer functions become (“closed-loop transfer functions”) [9]:

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

Even though the original open-loop system is stable, the closed-loop transfer functions can be unstable and contain right half-plane roots [9]. 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 [9]. 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) [9]. For stability investigation, phase margin test method is very easy for converter controller design [9].

3.2.1 Phase Margin Test

The aim of this test on $T(s)$, is to determine whether $1/(1 + T(s))$ contains RHP (right-half-plane) poles. The phase margin is defined as the change in phase shift required to make a closed loop system unstable [11].

The crossover frequency f_c is defined as the frequency where [9]

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

The phase margin φ_m is determined from the phase of $T(s)$ at f_c , as follows [9]:

$$\varphi_m = 180^\circ + \angle T(j2\pi f_c)$$

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 [9].

The phase margin also measures the system's tolerance to time delay [12]. The time delay can be 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 [12].

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 feed-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 signal 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 [12]. A negative phase margin means that the system is unstable [12].

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, a compensator network $G_c(s)$ can be added to modify $T(s)$ in order to meet all the specifications [9].

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 (K_i) decreases the rise time, increases both the overshoot and the settling time, and eliminates the steady-state error. In chapter 5, an opamp 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 GRAPHICAL USER INTERFACE (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 [10]. To perform these tasks, the user of the GUI does not have to create a script or type commands at the command line [10]. Often, the user does not have to know the details of the task at hand [10].

The GUI components can be menus, toolbars, push buttons, radio buttons, list boxes, and sliders [10]. In MATLAB, a GUI can also display data as plots, and can group related components [10].

➤ GUIDE

GUIDE, the MATLAB graphical user interface development environment, provides a set of tools for creating graphical user interfaces (GUIs) [10]. These tools simplify the process of laying out and programming GUIs [10].

➤ 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 [10]. It also enables the user to create menus and context menus for the GUI [10].

➤ Programming the GUI

When saving GUI layout, GUIDE automatically generates an M-file that the user can use to control how the GUI works [10]. 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 [10]. Using the M-file editor, the user can add code to the callbacks to perform the desired functions [10].

4.2 “Converter Design” GUI

In MATLAB Workspace, by typing “Converter_Design” GUI will be opened (Figure 14). 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 buck 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.

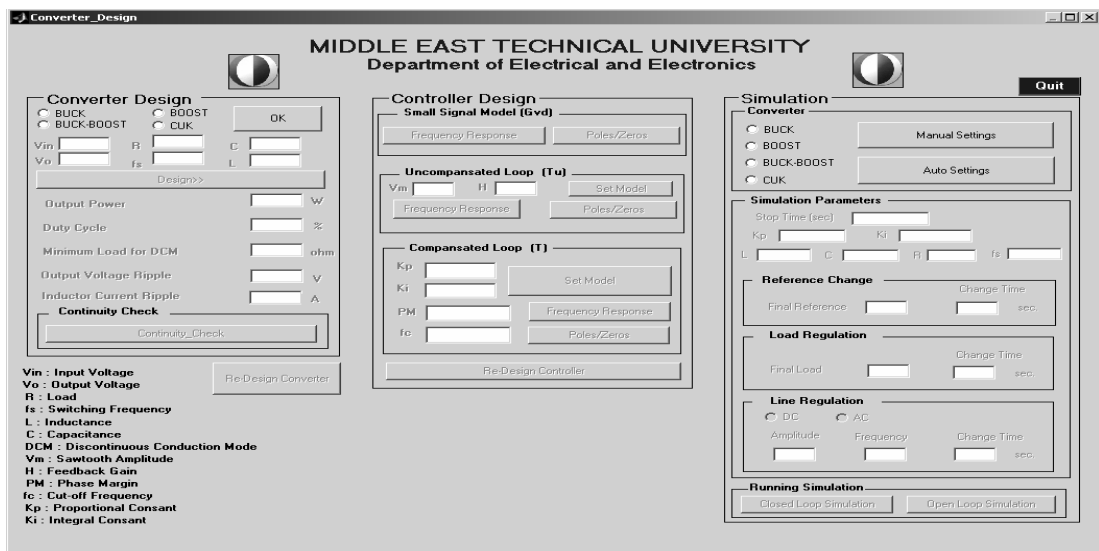


Figure 14 “Converter Design” GUI

Note-1: All actions can be performed by pressing buttons 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 occurring 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 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.

Not-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 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:

- V_m : 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 Buck Converter Test Box and Converter Circuitry

The general view of the buck converter test box is given in Figure 15. It contains open and closed loop control buttons and probes for external measurements. The functions of each section are shown in Figure 15.

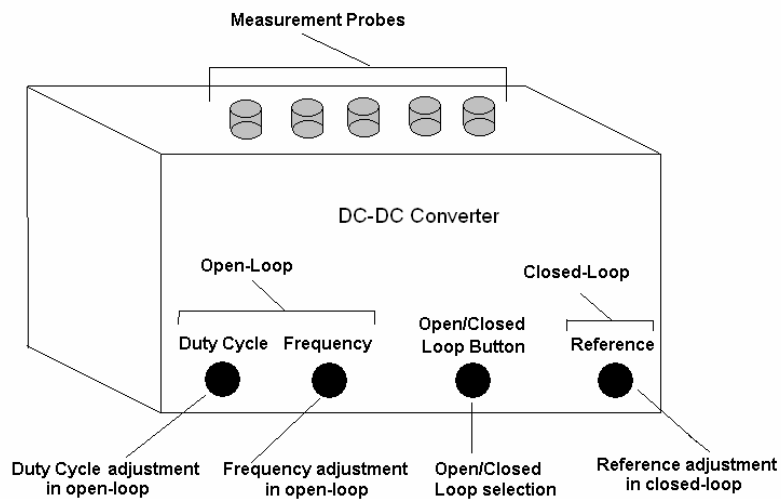


Figure 15 General view of the DC-DC converter test box

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

Table 2 Buck converter test box specification

Input Voltage	23 V-35V
Minimum Output Load	5 Ω
Inductor	220 μ H ($R_{\text{internal}} = 0.05 \Omega$)
Capacitor	100 μ F (ESR = 0.15 Ω)
Operation Frequency	7.7 kHz - 58 kHz
Maximum Duty Cycle	70 %

The view of the buck converter hardware is shown in Figure 16. The circuit consists of three main stages; power stage, PWM stage and compensator stage. The power stage consists of buck converter and “IR2125” MOSFET gate driver. In the compensator stage, op-amps are used to perform PI compensation. The PWM stage consists of “KA7552” IC and its components, which is used for production of PWM signals to “IR2125” gate driver.

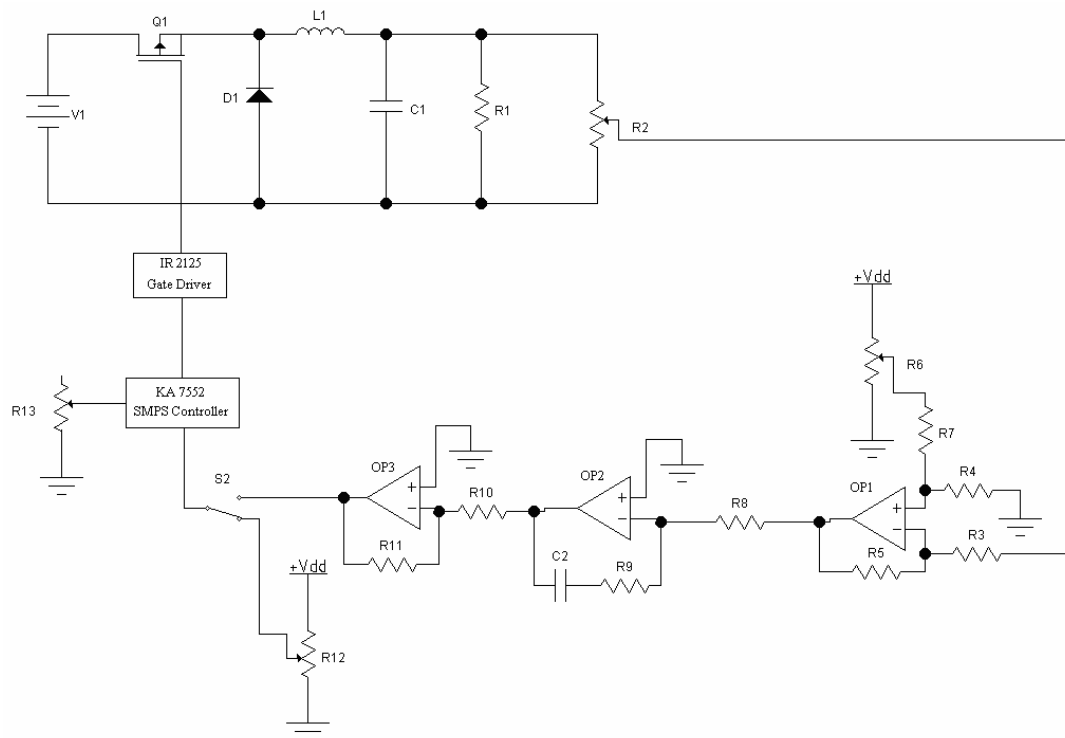


Figure 16 Hardware overview.

In the compensator stage, “OP1” opamp is a difference amplifier. The reference voltage that is adjusted with R_6 is extracted from output voltage that is scaled with R_2 . The result is applied to “OP2” opamp input.

“OP2” opamp is used for PI compensator. The transfer function of the PI compensator is given below:

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

where,

$$K_p = \frac{R_9}{R_8}$$

$$K_i = \frac{1}{R_8 C_2}$$

Because a negative voltage level is obtained at the output of “OP2” opamp, another opamp, “OP3”, is used as an inverting amplifier which has “ $-R_{11}/R_{10}$ ” conversion ratio.

A PI compensator was generated in accordance with the design needs given in “Design Example” Chapter. To realize this compensator, the following component values are used in circuitry:

- $R_8 = 330 \Omega$
- $C_2 = 4.7 \mu\text{F}$
- $R_9 = 673 \Omega$
- $R_{11} = R_{12} = 100 \text{ K } \Omega$

The related proportional and integral gains are:

- $K_p = 2.039$
- $K_i = 618.5$

“S2” switch select the operation of the circuit. If the switch is connected to the “OP3” output the circuit operates in closed loop; if it is connected to the “R₁₂”, the circuit operates in open loop. “R₁₂” adjusts the duty cycle of the PWM output in open loop.

“R₁₃” adjusts the frequency of the PWM signal. Notice that switching frequency can be adjusted both in the open loop and closed loop operations.

As gate driver, “IR2125 High and Low Side MOSFET Driver” IC is used. This driver has undervoltage lockout and cycle-by-cycle over current protection features. Applied over current protection circuitry is shown in Figure 17.

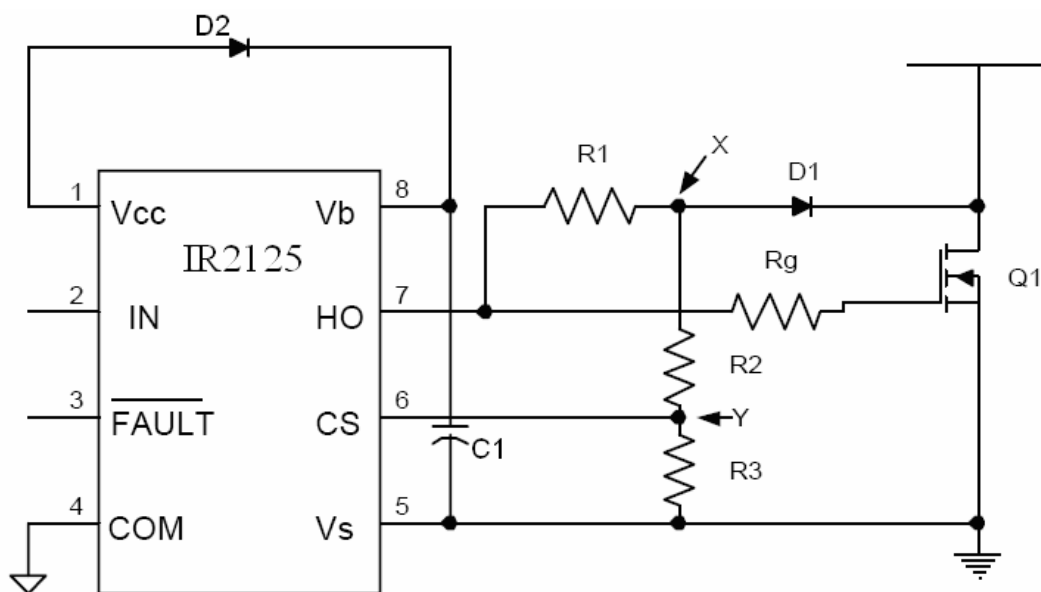


Figure 17 “IR2125” Current sensing circuit configuration.

In this circuit, “C₁” and “D₂” are bootstrap capacitor and bootstrap diode, respectively. “R_g” is the gate resistor. “R₁” is chosen 22 kΩ to make sure that no significant current is drawn from the HO output.

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 this thesis, DSS16-01A is used as D1 and D2 with have 0.64V forward voltage.

$$V_{DS} = I_S \cdot R_{DS}$$

“IRF530” MOSFET is used as power switch on converter circuitry. This model has 0.16 Ω internal on resistance. The circuit is designed for 10 A output current. So V_{DS} becomes 1.6 V, and V_X 2.24 V.

For “IR2125”, CS pin threshold is 250 mV, therefore R₂ and R₃ are chosen such that when V_X = 2.24V, then V_Y = 250mV.

$$V_Y = V_X \cdot R_3 / (R_2 + R_3) \quad R_2 \text{ is chosen } R_2 = 8 \text{ k}\Omega$$

$$R_3 = 1 \text{ k}\Omega$$

The following section will present the details in buck converter design by using “Converter Design” GUI as design and simulation tool. Real measurement will be given and verified with simulation results.

CHAPTER 6

SIMULATION AND EXPERIMENTAL RESULTS

The followings are simulation and measurement results of the designed and manufactured buck converter. Firstly, “Converter Design” GUI is used for simulation of the converter, then real measurements are taken. At the end of each section, simulation and measurement results are compared.

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

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

Step-3: The following design inputs are entered:

- $V_{in} = 30 \text{ V}$
- $V_o = 15 \text{ V}$
- $R = 13 \Omega$
- $f_s = 20000 \text{ Hz}$
- $C = 100 \mu\text{F}$
- $L = 220 \mu\text{H}$

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

- Output Power = 17.3077 W
- Duty Cycle = 50 %
- Minimum Load for DCM = 17.6 Ω
- Output Voltage Ripple = 215 mV
- Inductor Current Ripple = 1.70455 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 taken by using an oscilloscope. The followings are obtained simulation and measurement results.

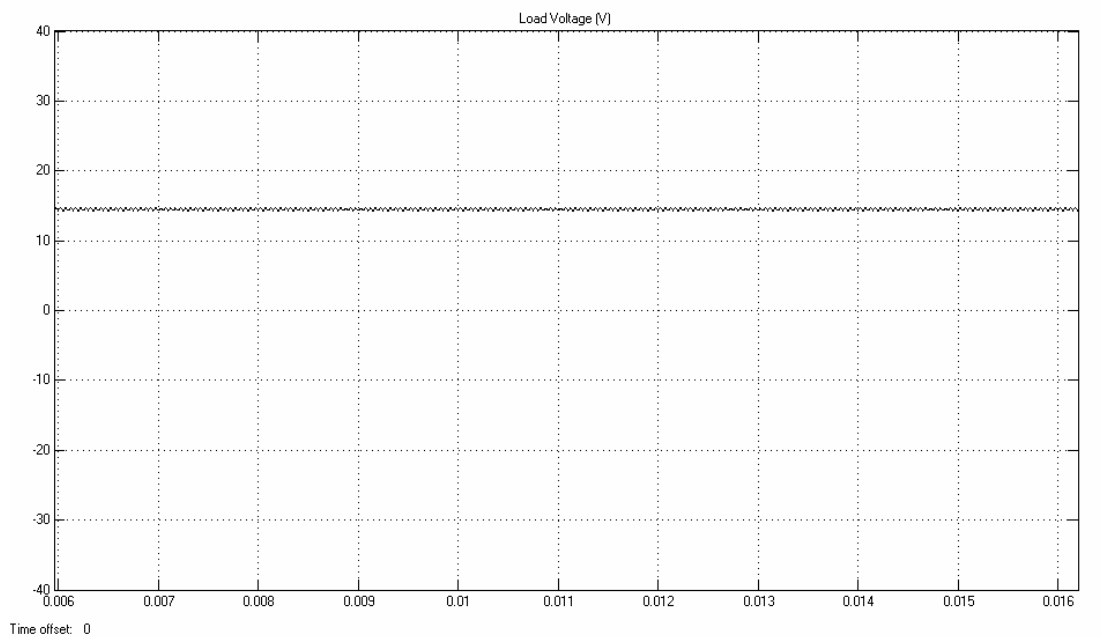


Figure 18 Simulation result - Buck converter output voltage (oscilloscope channel is at DC mode).

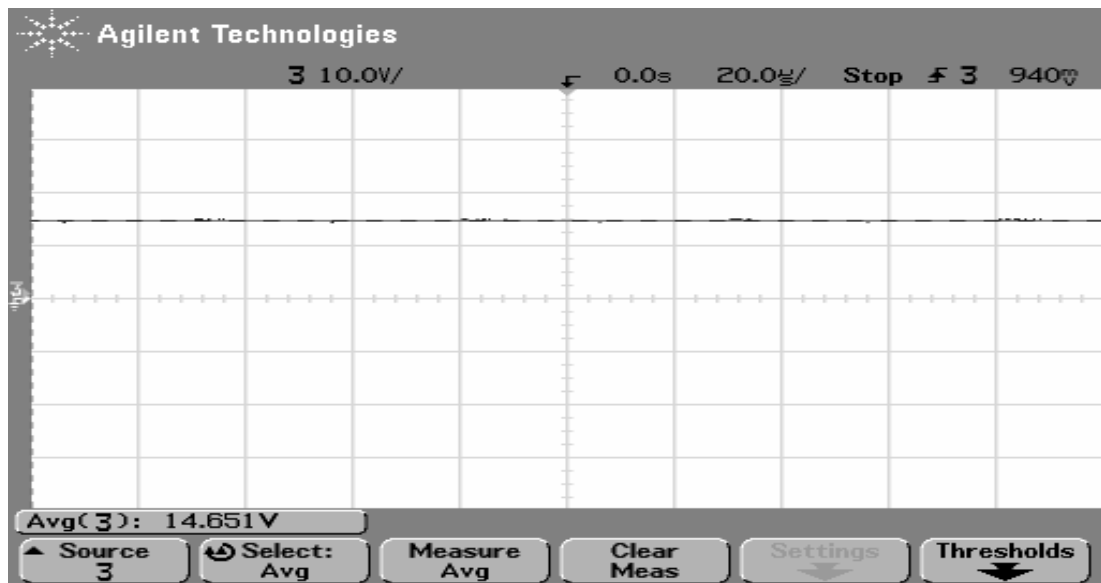


Figure 19 Measurement result-Buck converter output voltage (oscilloscope channel is at DC mode).

The following results are obtained:

- Simulation result: Output voltage is equal to 14.520 V DC
- Measurement result: Output voltage is equal to 14.651 V DC

It is seen that the desired 15 V DC output voltage cannot be obtained at the converter output. This may occur due to several reasons; most important are components internal losses and printed circuit board trace losses.

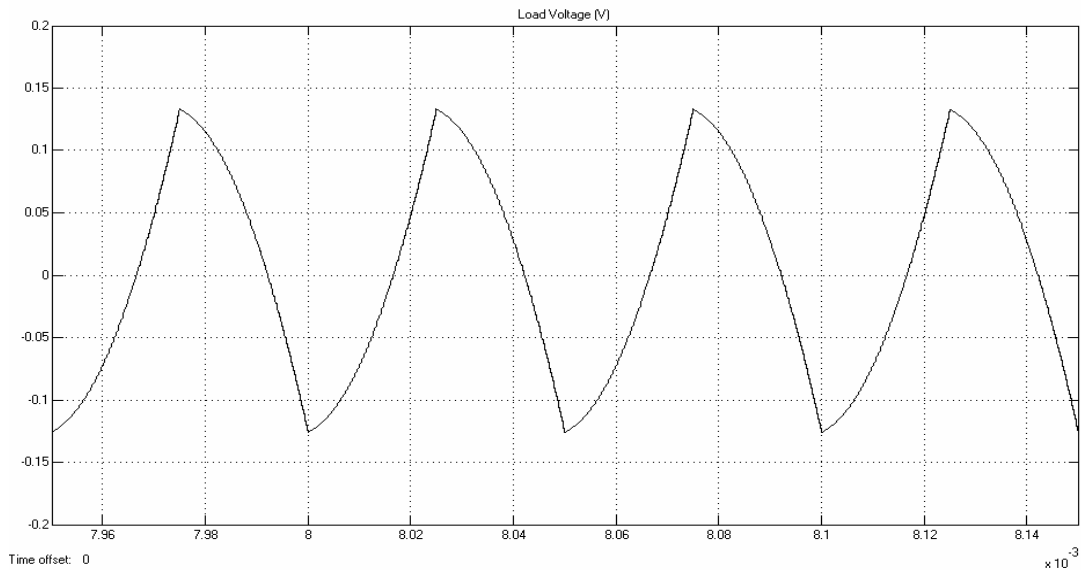


Figure 20 Simulation result-Buck converter output voltage (oscilloscope channel is at AC mode).

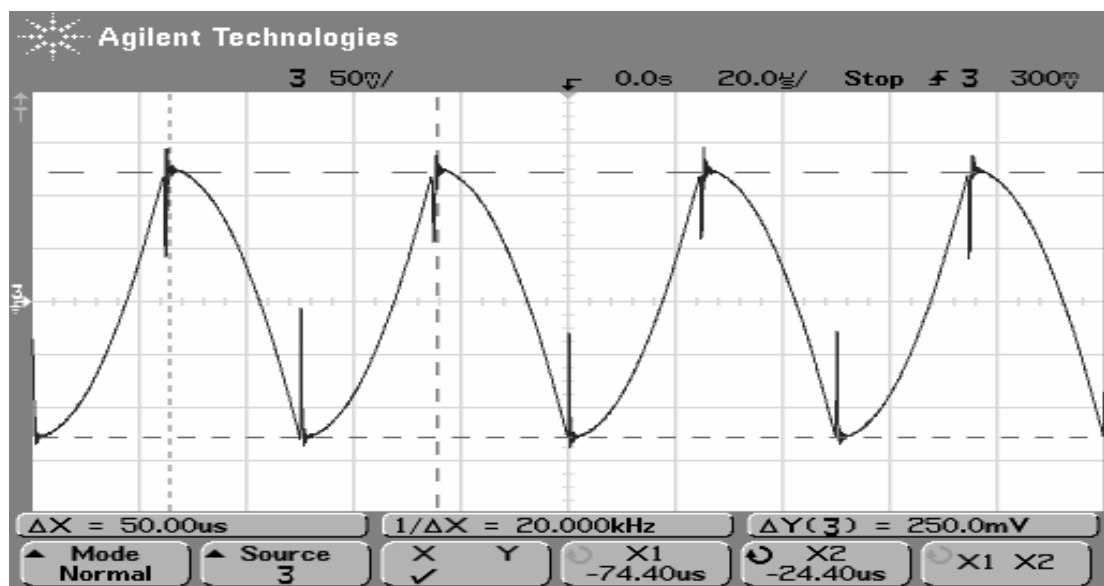


Figure 21 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).

The following results are obtained:

- Simulation result: Output voltage ripple is equal to 257 mV peak-to-peak AC.
- Measurement result: Output voltage is equal to 250 mV peak-to-peak AC.

It is seen that approximately 250 mV peak-to-peak output voltage ripple is obtained on the converter output. This ripple value depends on duty-cycle, operating frequency and output capacitor ESR (Equivalent Series Resistance). Increase in ESR value also increases the output voltage ripple. In the manufactured converter, a capacitor with 0.15 Ω ESR value is used.

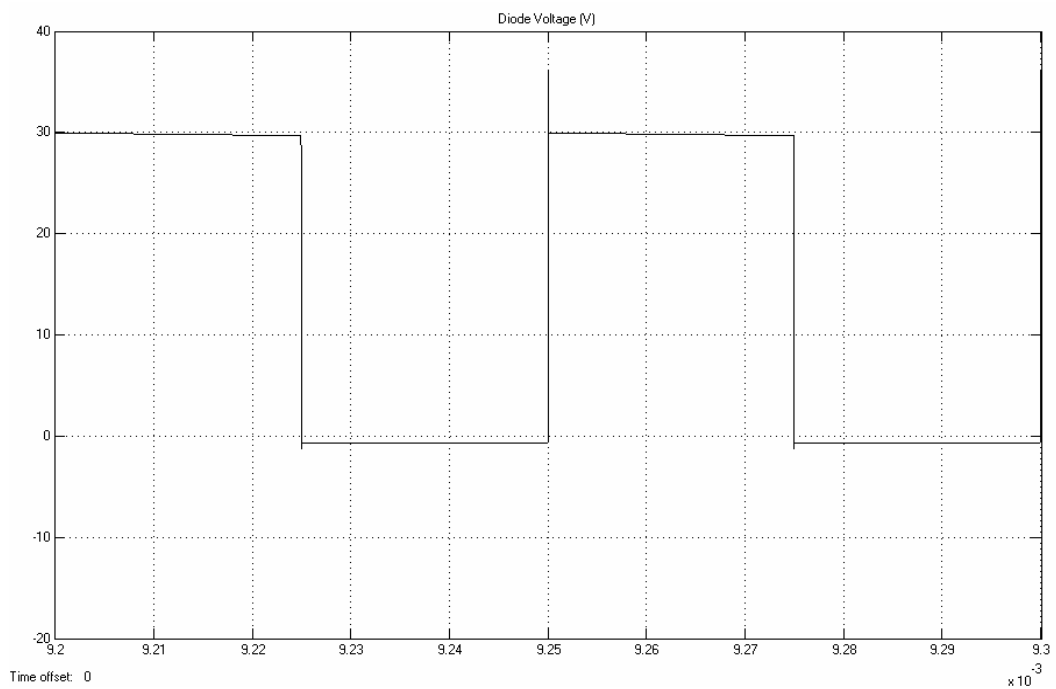


Figure 22 Simulation result-Buck converter diode voltage.

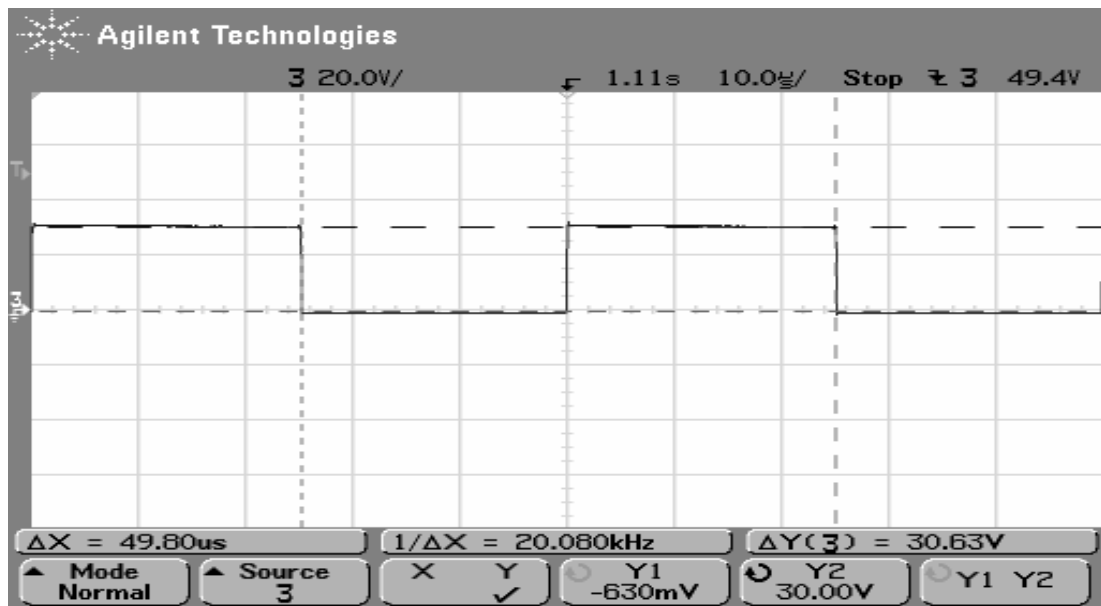


Figure 23 Measurement result-Buck converter diode voltage.

The following results are obtained:

- Simulation result: Diode voltage is equal to 30 V at diode off-state and to -630 mV (diode on-state voltage drop) at diode on-state.
- Measurement result: Diode voltage is equal to 30 V at diode off-state and to -630 mV (diode on-state voltage drop) at diode on-state.

It is seen that when diode is forward biased (or switch is turned-off), there exist an on-state voltage drop on it. On the other state (or switch is turned-on), it exhibits open-circuit characteristic.

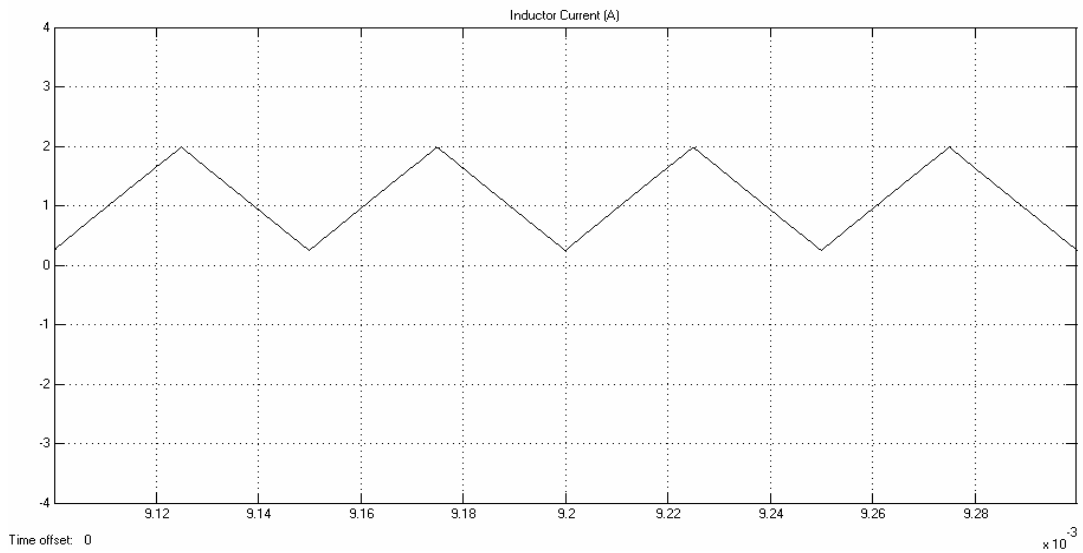


Figure 24 Simulation result-Buck converter inductor current.

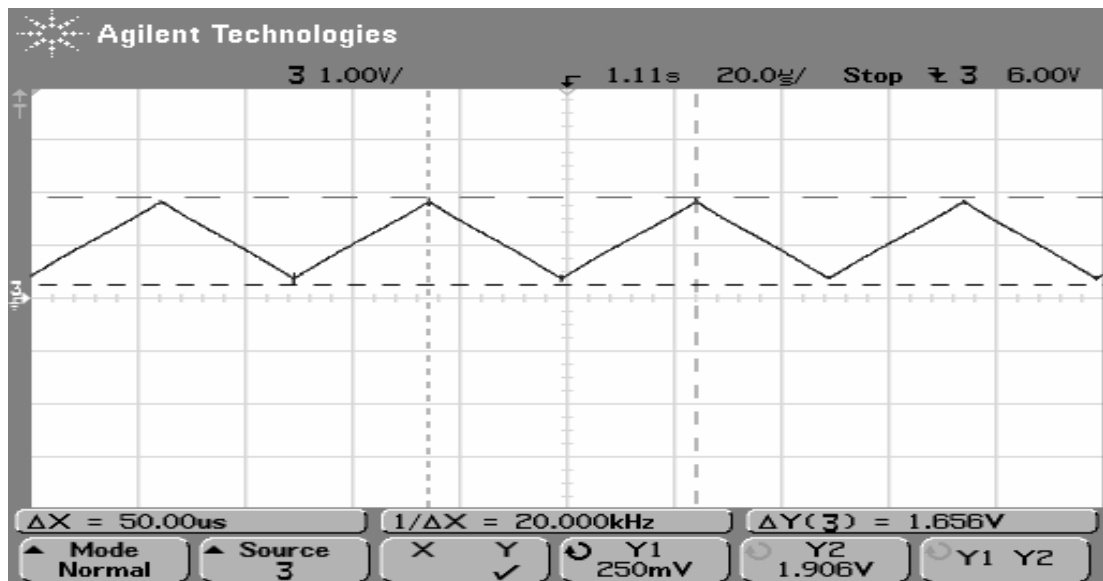


Figure 25 Measurement result-Buck converter inductor current.

The following results are obtained:

- Simulation result: Inductor current ripple is equal to 1.7 A

- Measurement result: Inductor current ripple is equal to 1.656 A

It is known that the converter operates in CCM. The positive inductor current during the switching period verifies CCM operation.

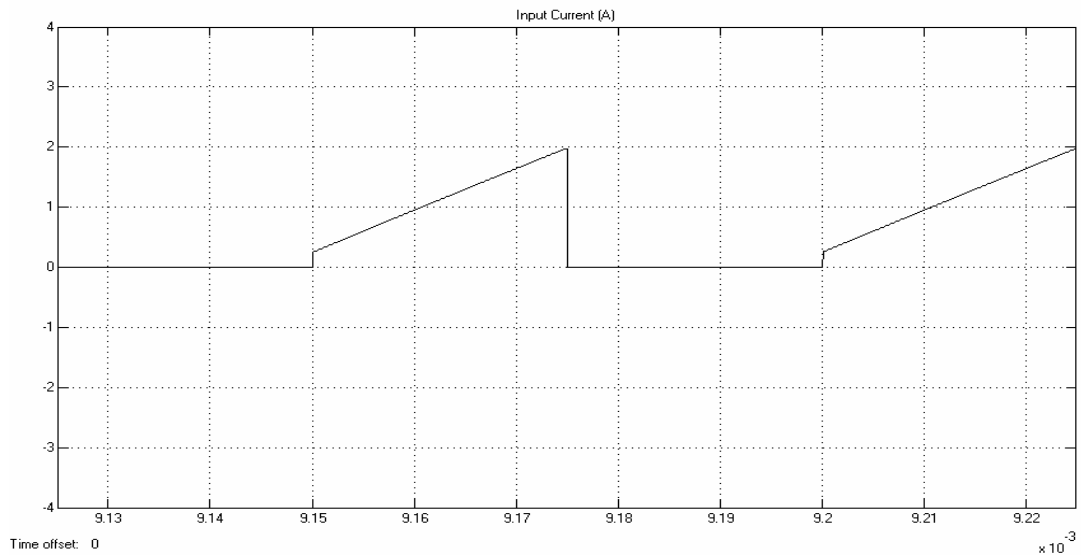


Figure 26 Simulation result-Buck converter input current.

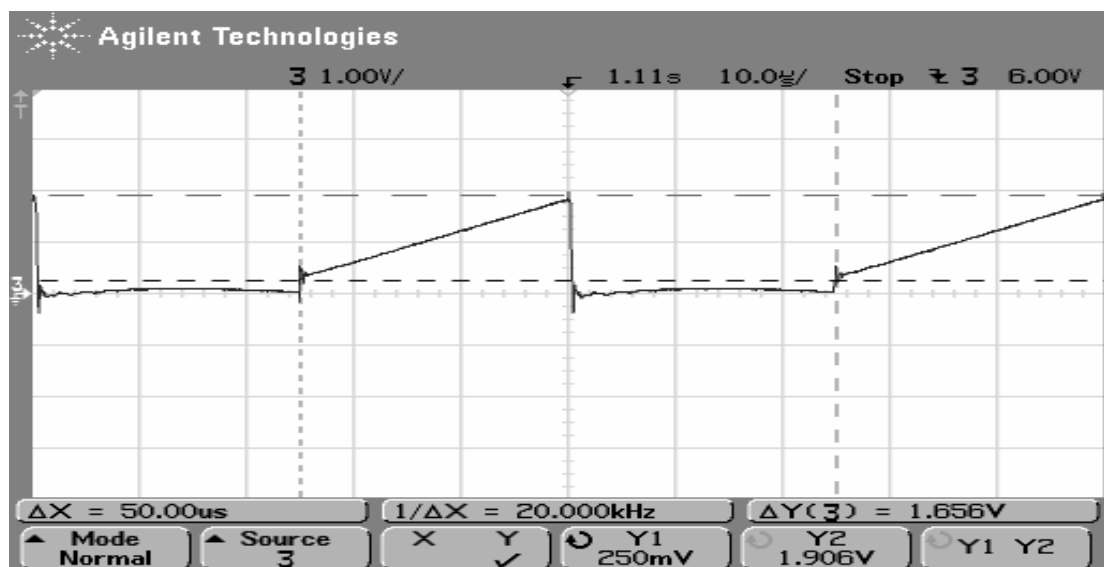


Figure 27 Measurement result-Buck converter input current.

The following results are obtained:

- Simulation result: Input current ripple is equal to 1.7 A
- Measurement result: Inductor current ripple is equal to 1.656 A

It is known that the converter operates in CCM. The positive input current during switch is turned-on verifies CCM operation.

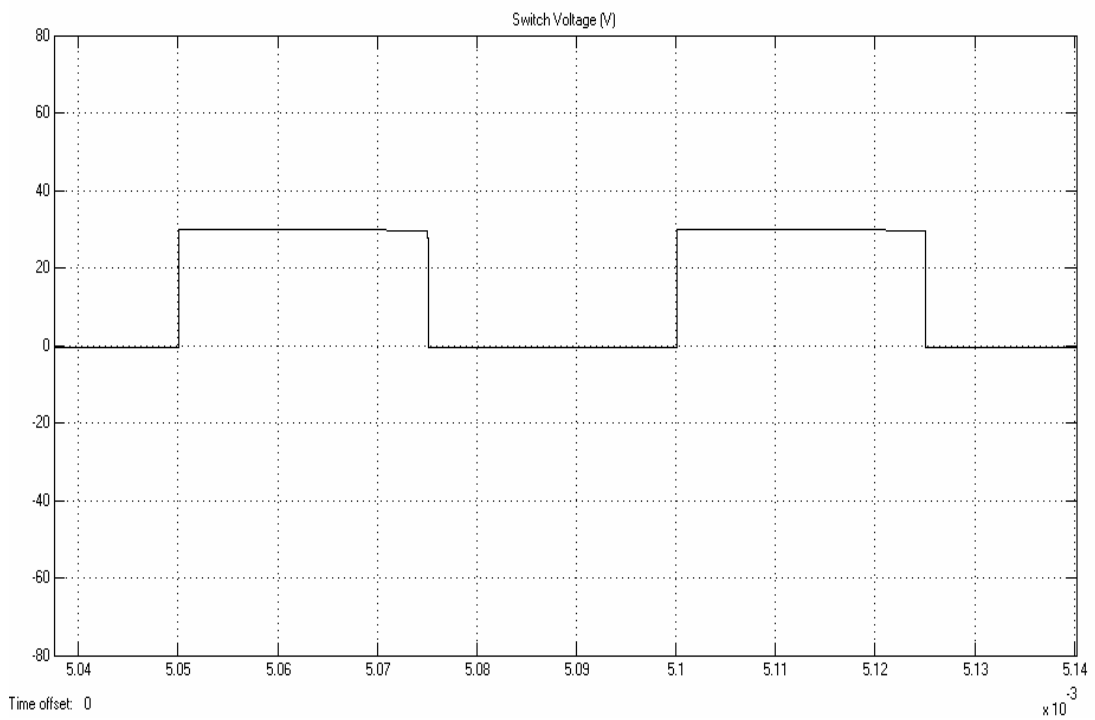


Figure 28 Simulation result-Buck converter switch voltage.

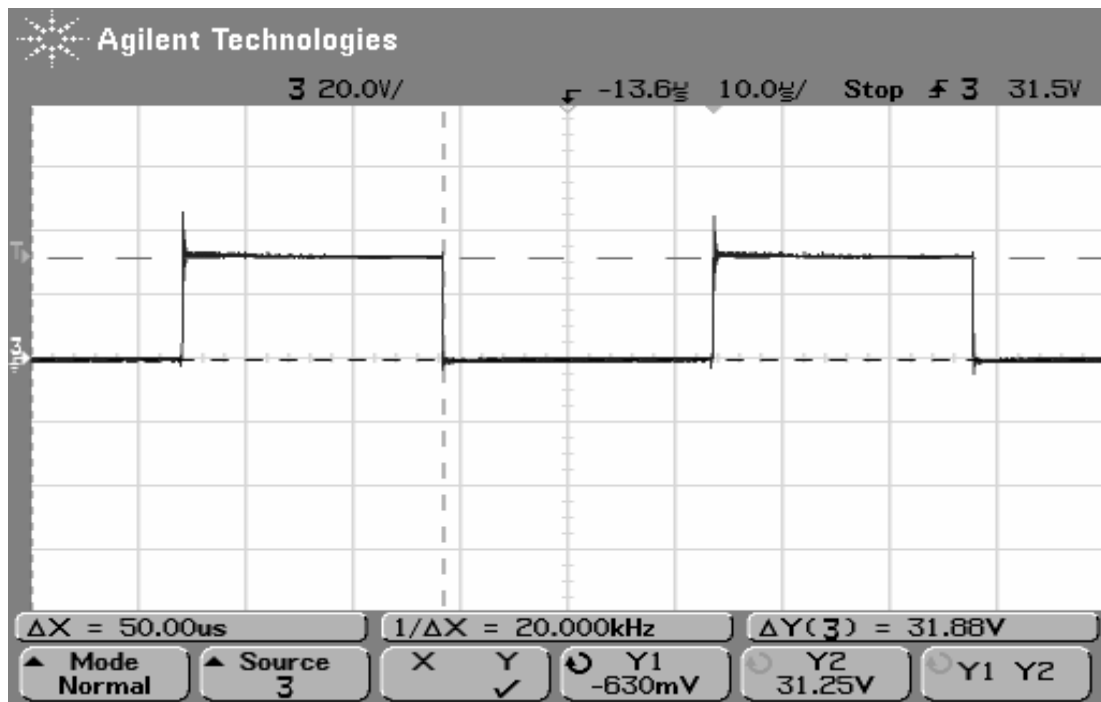


Figure 29 Measurement result-Buck converter switch voltage.

The following results are obtained:

- Simulation result: Switch voltage is equal to 31.2 V at switch off-state and to -630 mV (switch on-state voltage drop) at switch on-state.
- Measurement result: Switch voltage is equal to 30 V at switch off-state and to -630 mV (switch on-state voltage drop) at switch on-state.

It is seen that when switch is turned-on there exist an on-state voltage drop on it. On the other state (switch is turned-off), it exhibits open-circuit characteristic.

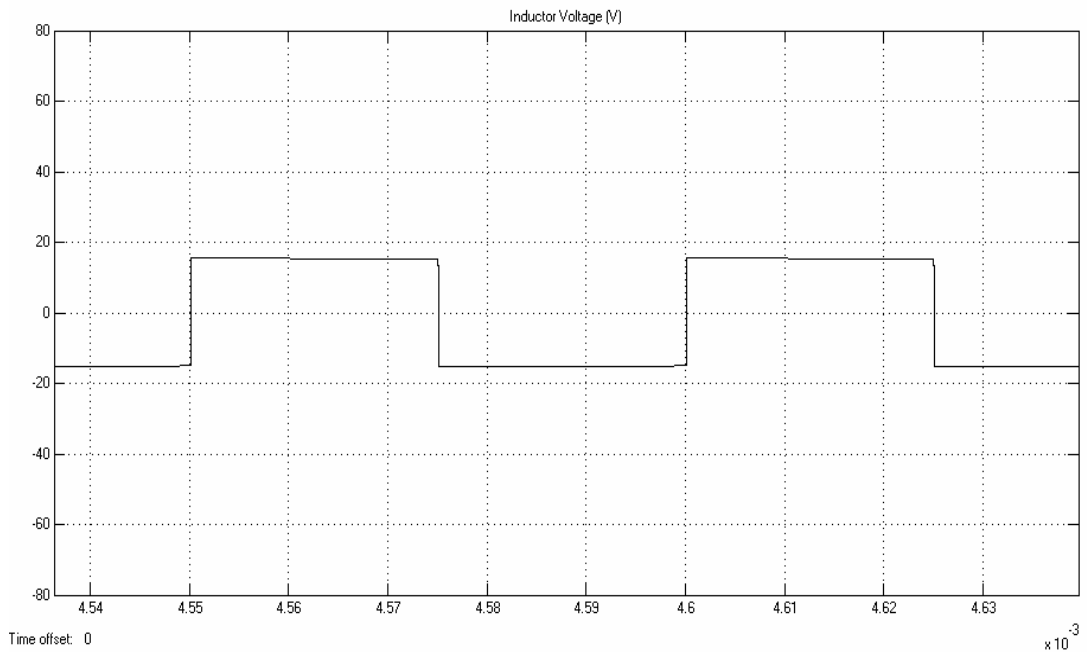


Figure 30 Simulation result-Buck converter inductor voltage.

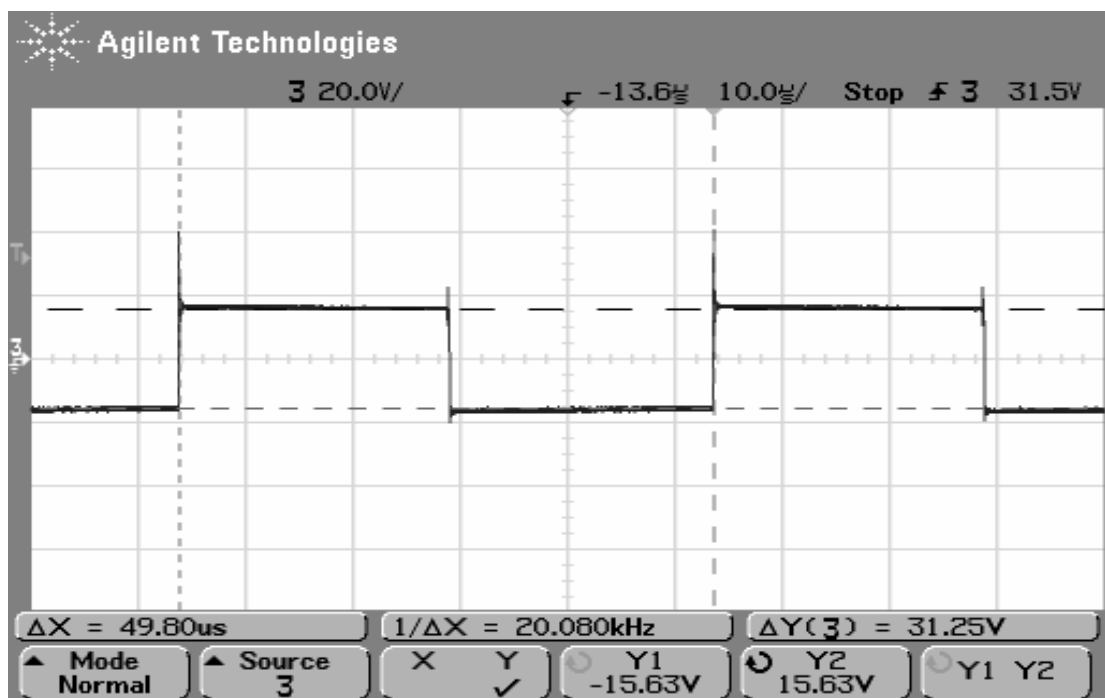


Figure 31 Measurement result-Buck converter inductor voltage.

The following results are obtained:

- Simulation result: Inductor voltage is equal to 15.5 V at switch off-state and to -15.5 V at switch on-state.
- Measurement result: Inductor voltage is equal to 15.63 V at switch off-state and to -15.63 V at switch on-state.

It is known that increasing load causes discontinuity if all the other parameters remain constant. In the following steps, load will be increased and it is desired to obtain discontinuity.

Step-8: “Re-design Converter” button is pressed.

Step-9: The following design inputs are entered;

- $V_{in} = 30 \text{ V}$
- $V_o = 16.8 \text{ V}$
- $R = 25 \Omega$
- $f_s = 20000 \text{ Hz}$
- $C = 100 \mu\text{F}$
- $L = 220 \mu\text{H}$

Step-10: “Design” button is pressed. The following design outputs are obtained;

- Output Power = 11.28 W
- Duty Cycle = 50 %
- Minimum Load for DCM = 20 Ω
- Output Voltage Ripple = 239 mV
- Inductor Current Ripple = 1.502 A

Step-11: “Continuity Check” button is pressed and it is seen that the designed converter operates in DCM (discontinuous conduction mode).

Step-12: “Auto Settings” button is pressed to set the simulation parameters.

Step-13: “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 followings are simulation and measurement results.

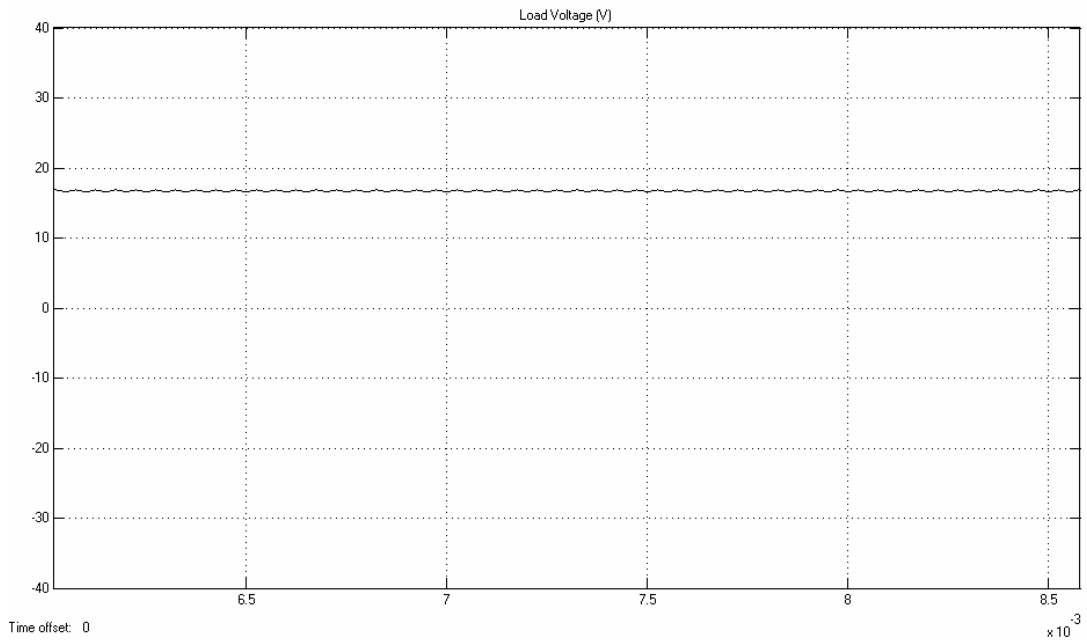


Figure 32 Simulation result-Buck converter output voltage (oscilloscope channel is at DC mode).

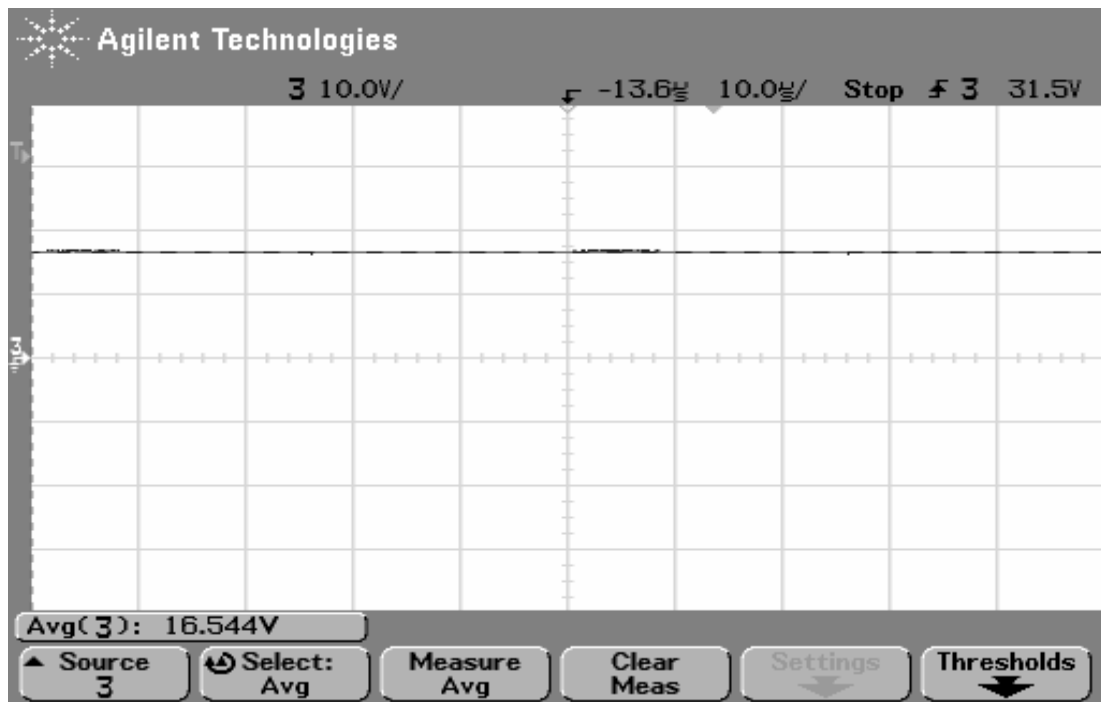


Figure 33 Measurement result-Buck converter output voltage.

The following results are obtained:

- Simulation result: Output voltage is equal to 16.75 V DC
- Measurement result: Output voltage is equal to 16.544 V DC

It is known that the output voltage of a buck converter which operates in CCM with a specific duty-cycle does not remain constant if discontinuity occurs by load increasement. So, these measurement and simulation results show that the output voltage increasement is due to the discontinuity.

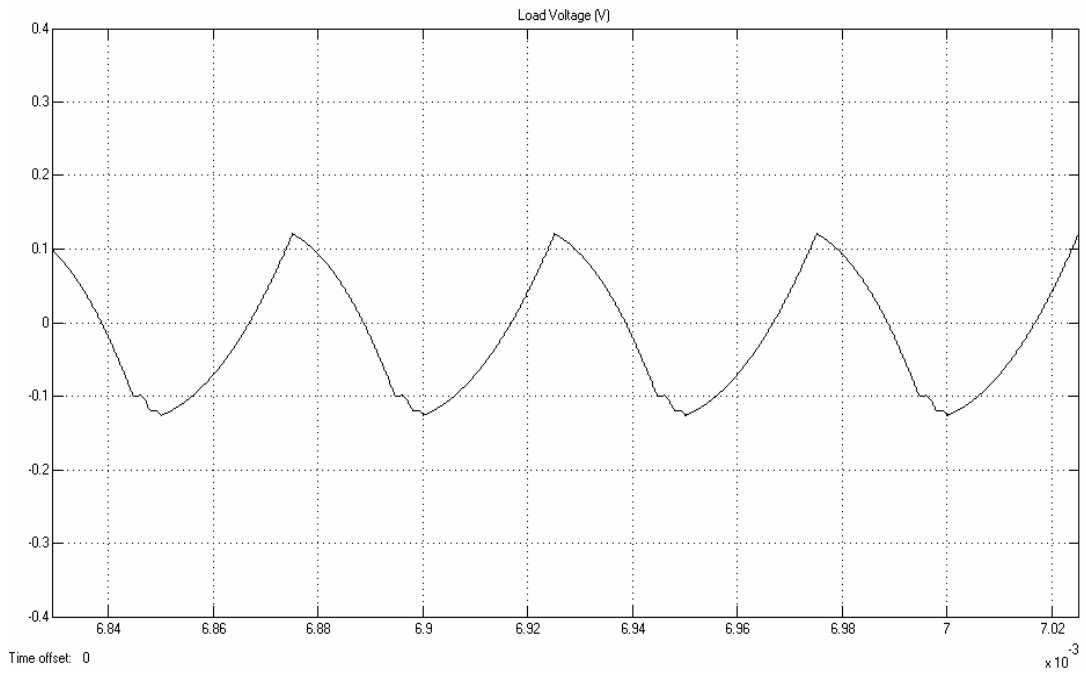


Figure 34 Simulation result-Buck converter output voltage (oscilloscope channel is at AC mode).

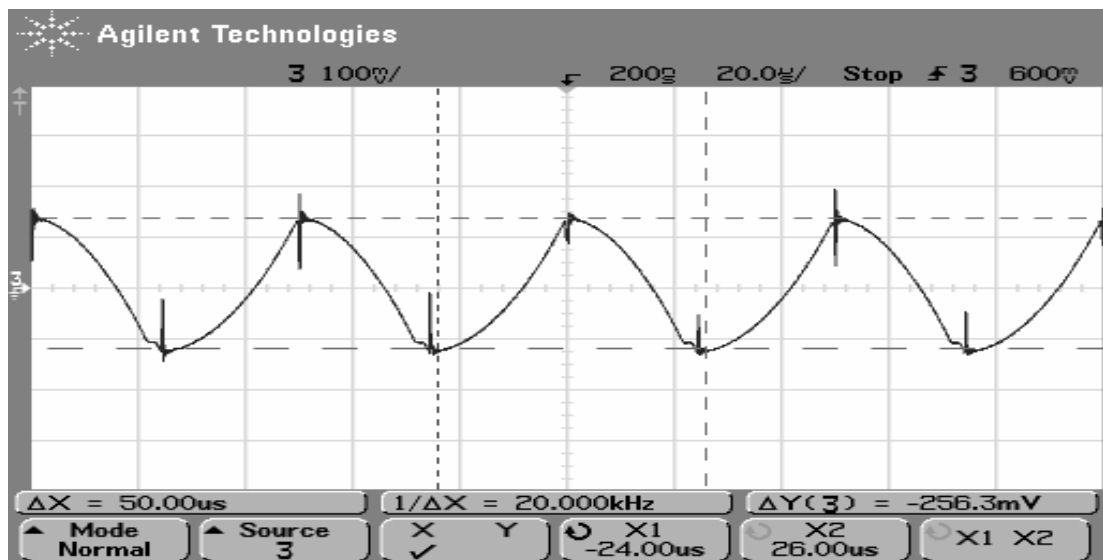


Figure 35 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).

The following results are obtained:

- Simulation result: Output voltage ripple is equal to 245 mV peak-to-peak AC.
- Measurement result: Output voltage is equal to 256 mV peak-to-peak AC.

It is seen that not a great change occurs in the output voltage ripple value when discontinuity occurs. This is due to the constant duty-cycle, frequency and capacitance ESR.

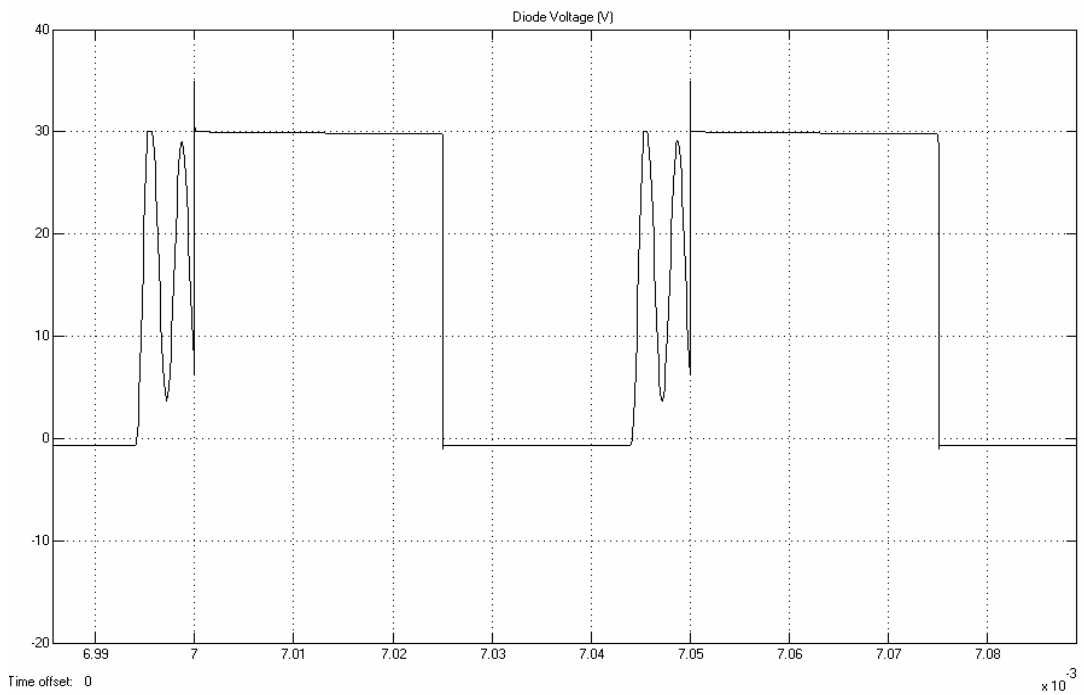


Figure 36 Simulation result-Buck converter diode voltage.

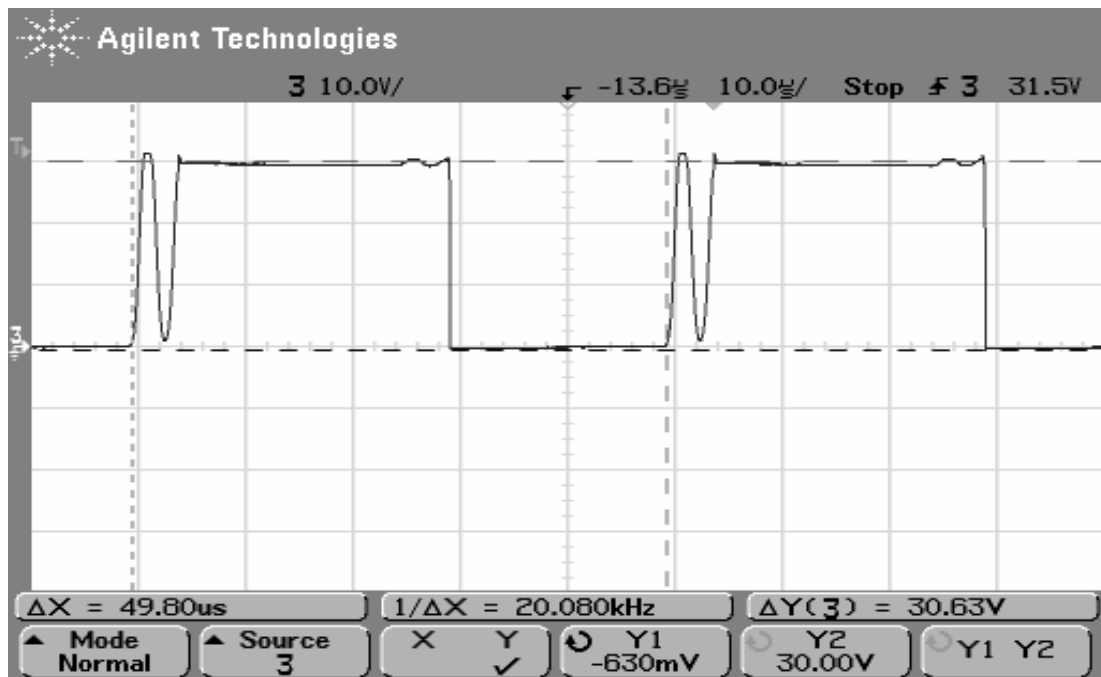


Figure 37 Measurement result-Buck converter diode voltage.

The following results are obtained:

- Simulation result: Diode voltage is equal to 30 V at diode off-state and to -630 mV (diode on-state voltage drop) at diode on-state.
- Measurement result: Diode voltage is equal to 30 V at diode off-state and to -630 mV (diode on-state voltage drop) at diode on-state.

Discontinuity can be also observed from diode voltage waveform [13]. At discontinuous mode operation, as seen from the results, there is parasitic oscillation on the diode voltage [13]. This is because at the moment the inductor current becomes zero, the diode voltage should adopt the output voltage, and the diode current should remain zero [13]. Nevertheless, for real switches, a network, consisting of parasitic capacitances C_{OS} (which is equal to C_{OSS} , for MOSFETs) of the switch and C_D of the diode, and the inductor L (Figure 38) starts the oscillating at that instant.

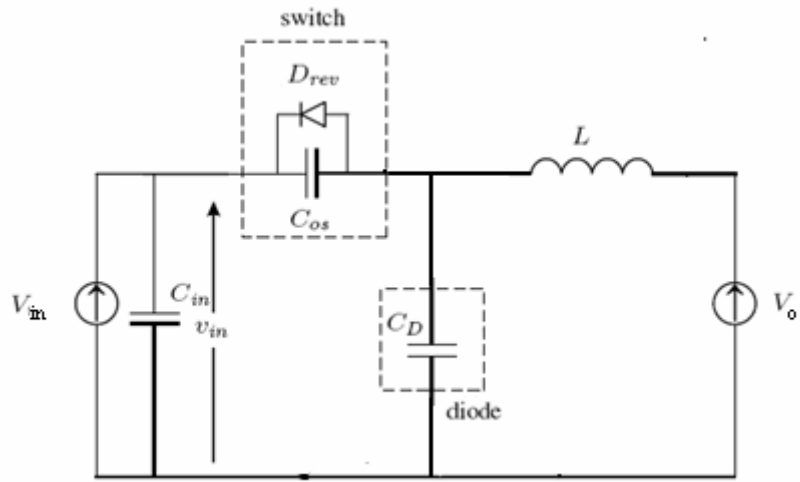


Figure 38 Parasitic network causing oscillations [13]

The diode voltage oscillation is described approximately as [13]:

$$V_D(t) = V_{in} \cos(\omega_n(t - t_2))$$

where,

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

and t_2 is the time when oscillation starts [13].

The capacitance C_n , in these expressions is equal to the parallel connection of the switch capacitance and the diode capacitance [13]. The oscillation is ended when the switch is turned on again [13]. For low duty-ratios, this interval may take several oscillation cycles [13].

The followings are the designed buck converter switch and diode parasitics [13]. These values are taken from the component datasheets [13]:

- C_{oss} of MOSFET (IRF530) is equal to 450 pF
- C_D of diode (DSS16-01A) is equal 250 pF

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

$$\omega_n = 2548200 \text{ rad/s}$$

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

$$\omega_n = 2513300 \text{ rad/s}$$

So, simulation and real measurement verify each other.

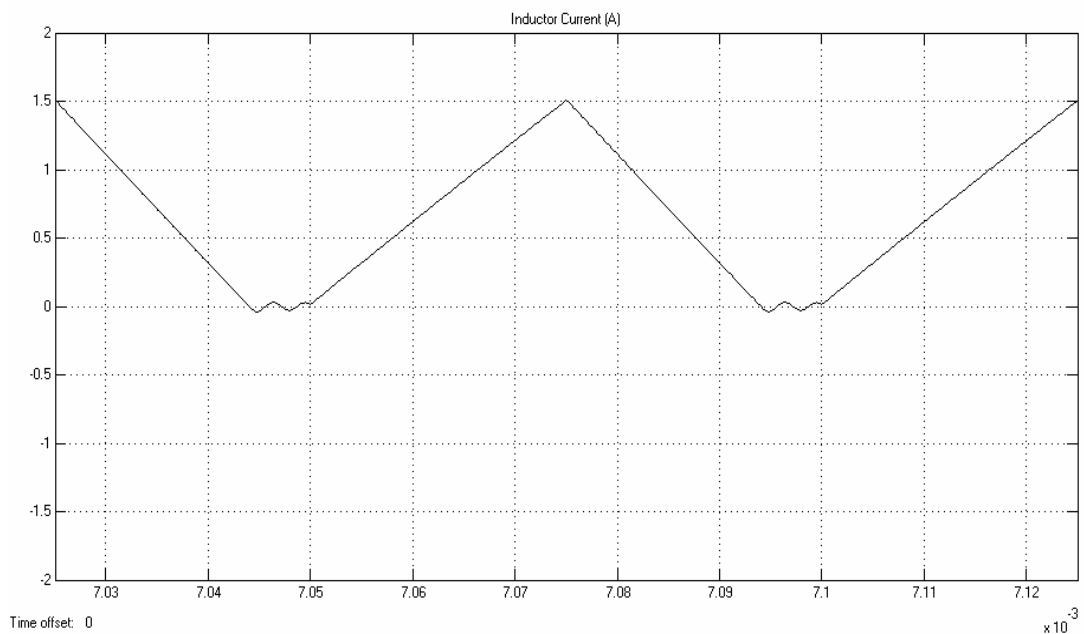


Figure 39 Simulation result-Buck converter inductor current.

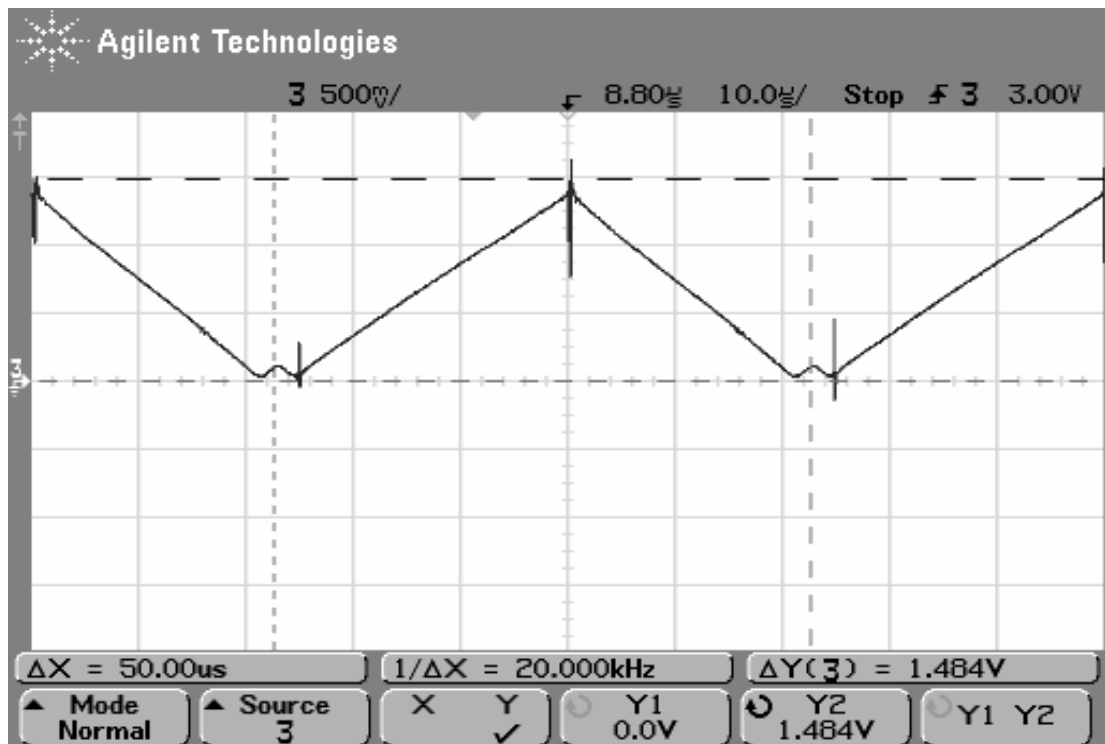


Figure 40 Measurement result-Buck converter inductor current.

The following results are obtained:

- Simulation result: Inductor current ripple is equal to 1.5 A.
- Measurement result: Inductor current ripple is equal to 1.484 A.

It is known that the converter operates in DCM. Zero inductor current values during the switching period verify DCM operation.

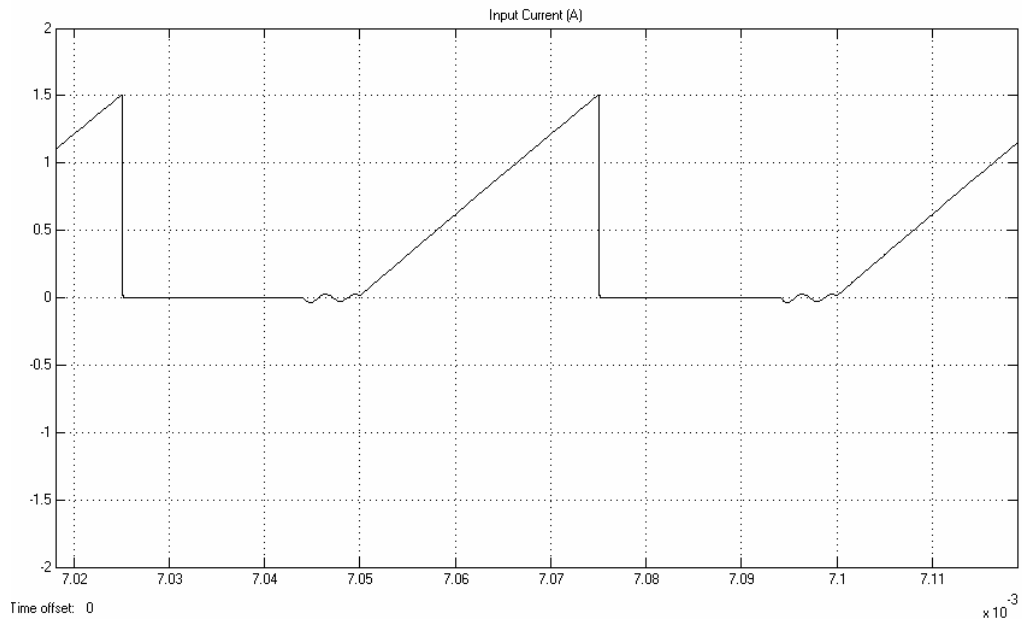


Figure 41 Simulation result-Buck converter input current.

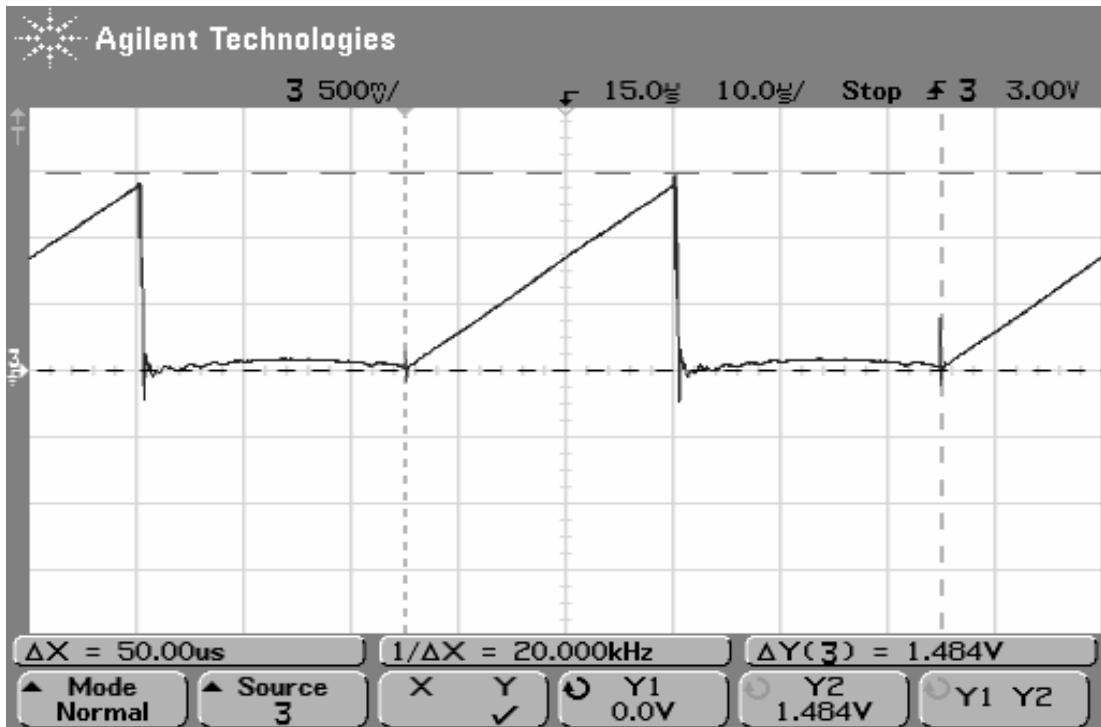


Figure 42 Measurement result-Buck converter input current.

The following results are obtained:

- Simulation result: Input current ripple is equal to 1.5 A.
- Measurement result: Input current ripple is equal to 1.484 A.

It is known that the converter operates in DCM. Zero input current values when switch is still turned-on verify DCM operation.

The followings are the other obtained waveforms.

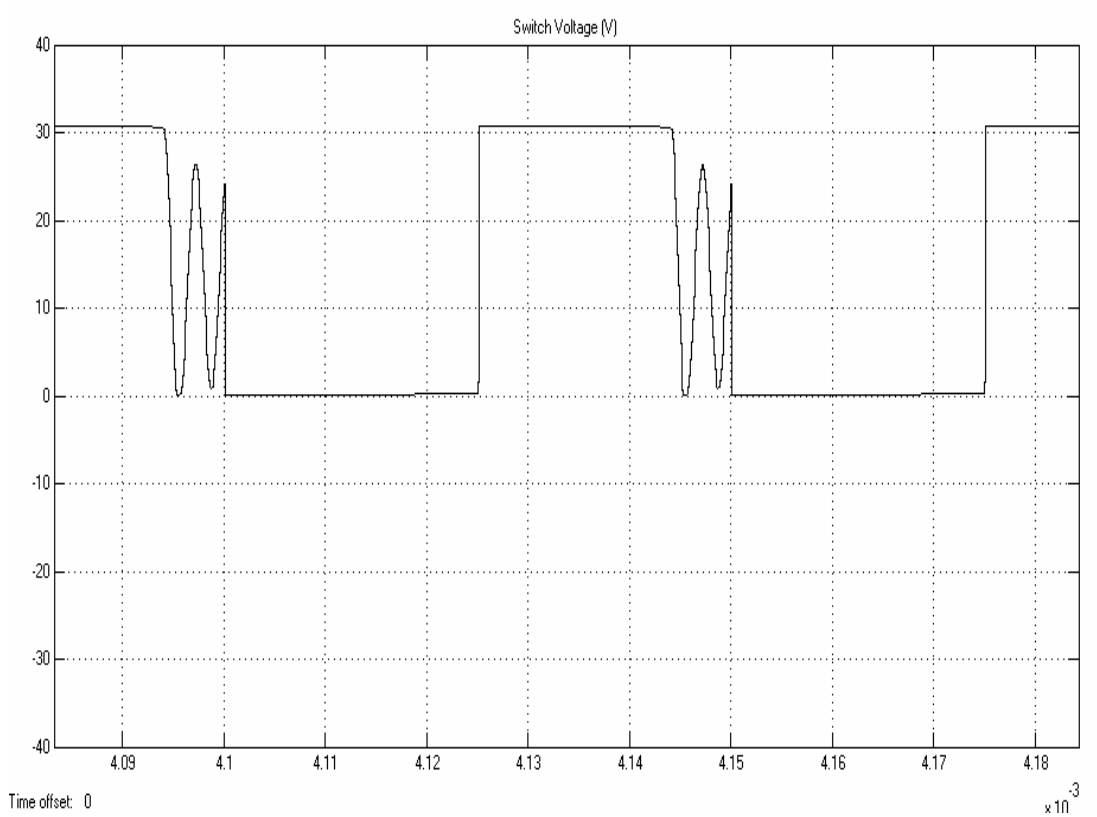


Figure 43 Simulation result-Buck converter switch voltage.

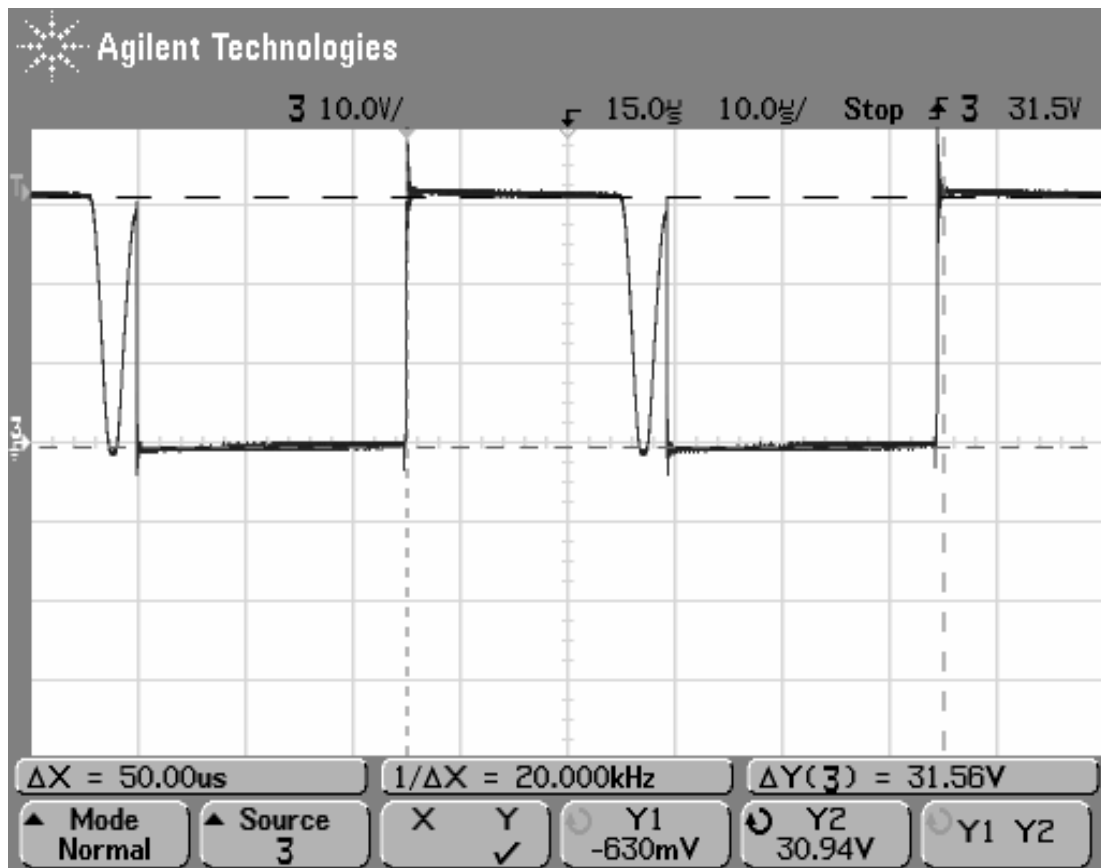


Figure 44 Measurement result-Buck converter switch voltage.

The following results are obtained:

- Simulation result: Switch voltage is equal to 30 V at switch off-state and to -630 mV (switch on-state voltage drop) at switch on-state.
- Measurement result: Switch voltage is equal to 30.94 V at switch off-state and to -630 mV (switch on-state voltage drop) at switch on-state.

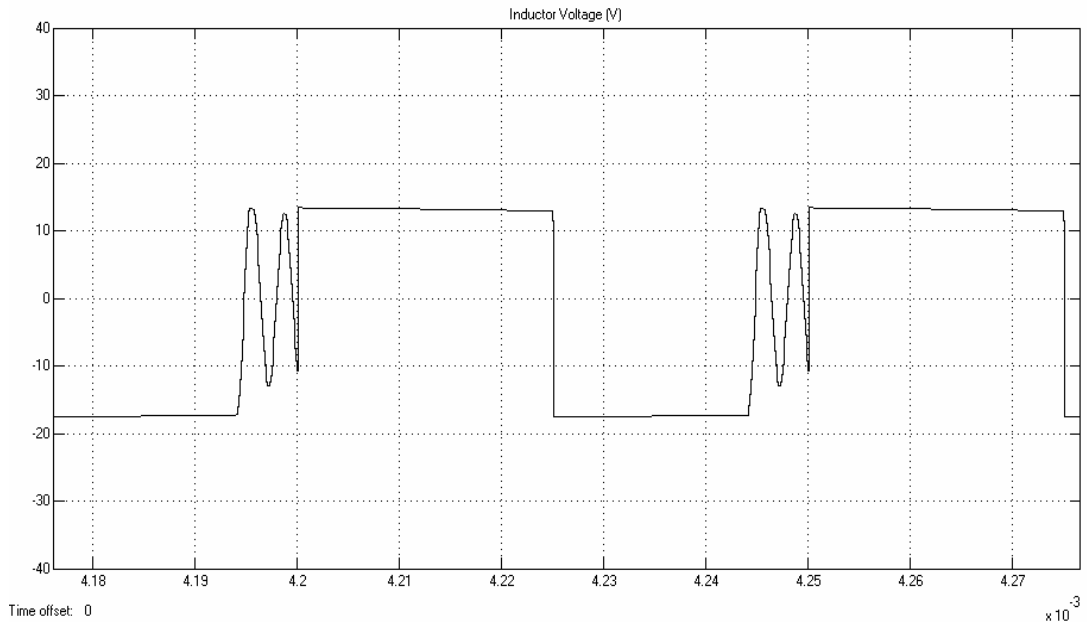


Figure 45 Simulation result-Buck converter inductor voltage.

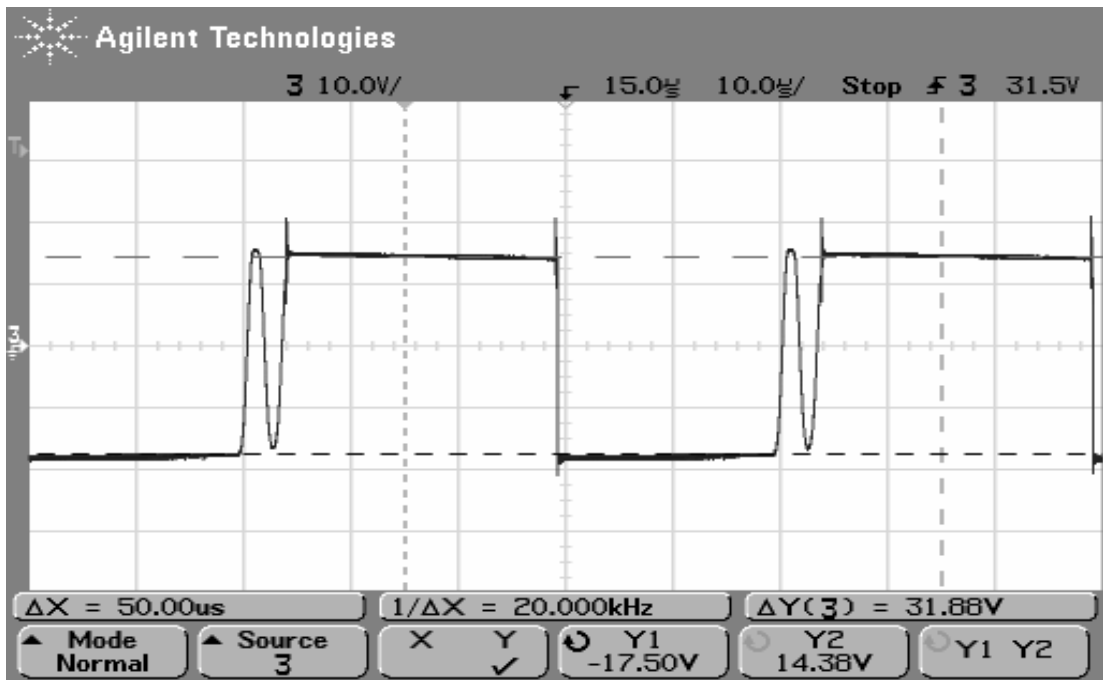


Figure 46 Measurement result-Buck converter inductor voltage.

The following results are obtained:

- Simulation result: Inductor voltage is equal to 13.8 V at switch off-state and to -17.5 V at switch on-state.
- Measurement result: Inductor voltage is equal to 14.38 V at switch off-state and to -17.5 V at switch on-state.

It is known that increasing the switching frequency causes continuity if all the other parameters remain constant. In the following steps, switching frequency will be increased and then it is desired to provide continuity again.

Step-14: The following design inputs are entered:

- $V_{in} = 30 \text{ V}$
- $V_o = 15 \text{ V}$
- $R = 25 \Omega$
- $f_s = 50000 \text{ Hz}$
- $C = 100 \mu\text{F}$
- $L = 220 \mu\text{H}$

Step-15: “Design” button is pressed. The following design outputs are obtained:

- Output Power = 9 W
- Duty Cycle = 50 %
- Minimum Load for DCM = 44 Ω
- Output Voltage Ripple = 100 mV
- Inductor Current Ripple = 0.681

Step-16: “Continuity Check” button is pressed and it is seen that the designed converter operates in CCM (continuous conduction mode).

Step-17: “Auto Settings” button is pressed to set the simulation parameters.

Step-18: “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 followings are simulation and measurement results.

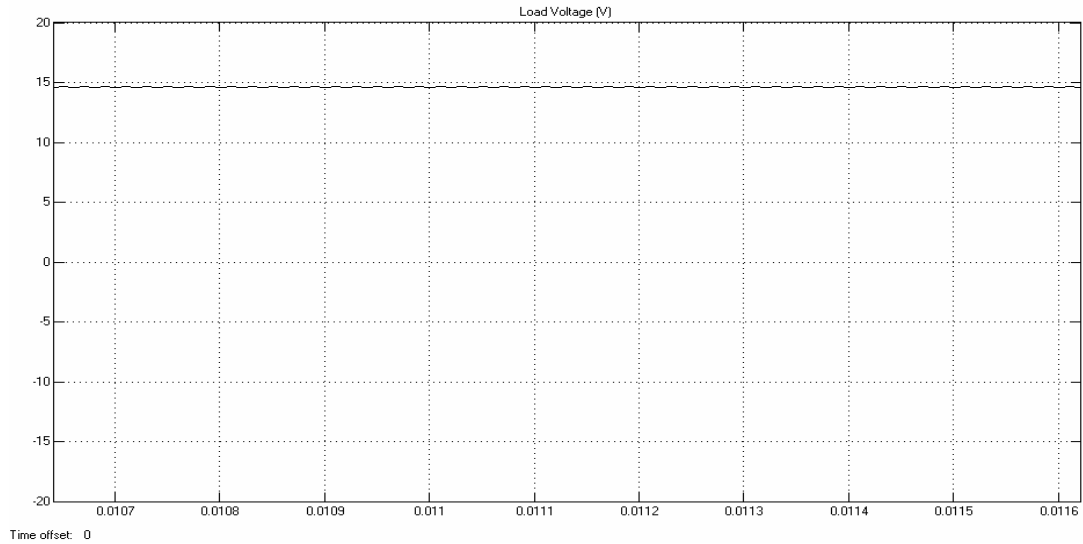


Figure 47 Simulation result-Buck converter output voltage (oscilloscope channel is at DC mode).

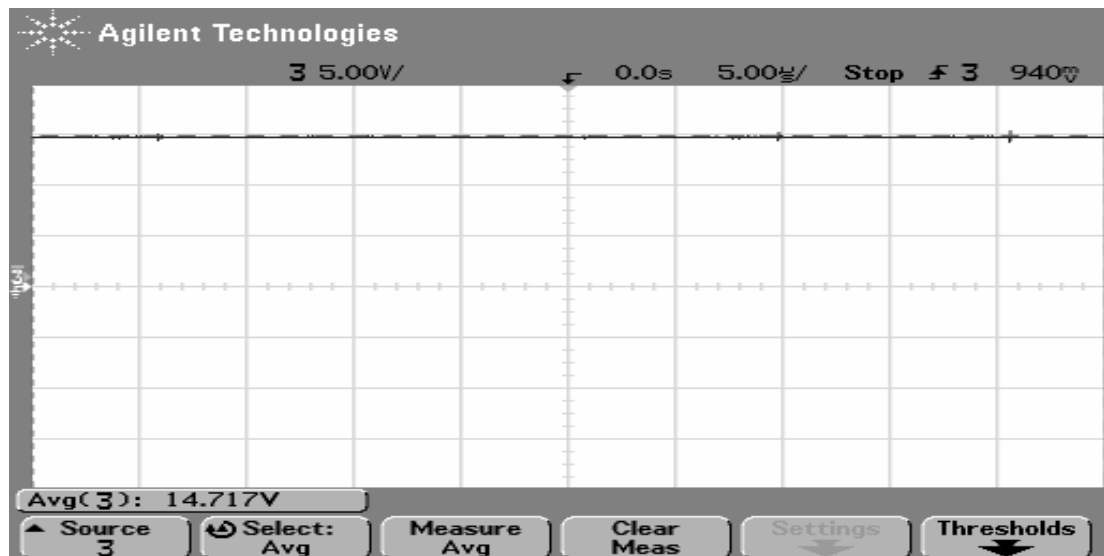


Figure 48 Measurement result-Buck converter output voltage (oscilloscope channel is at DC mode).

The following results are obtained:

- Simulation result: Output voltage is equal to 14.6 V DC.
- Measurement result: Output voltage is equal to 14.717 V DC.

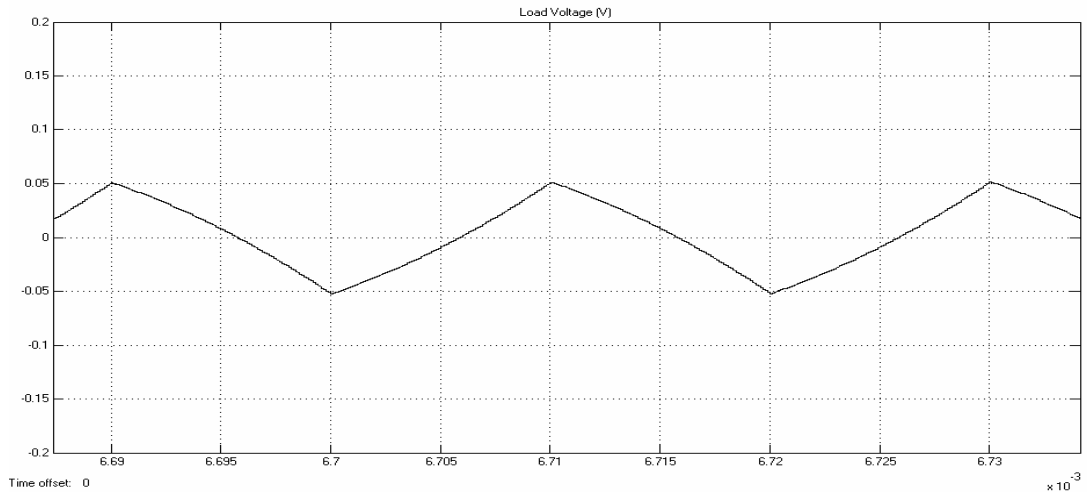


Figure 49 Simulation result-Buck converter output voltage (oscilloscope channel is at AC mode).

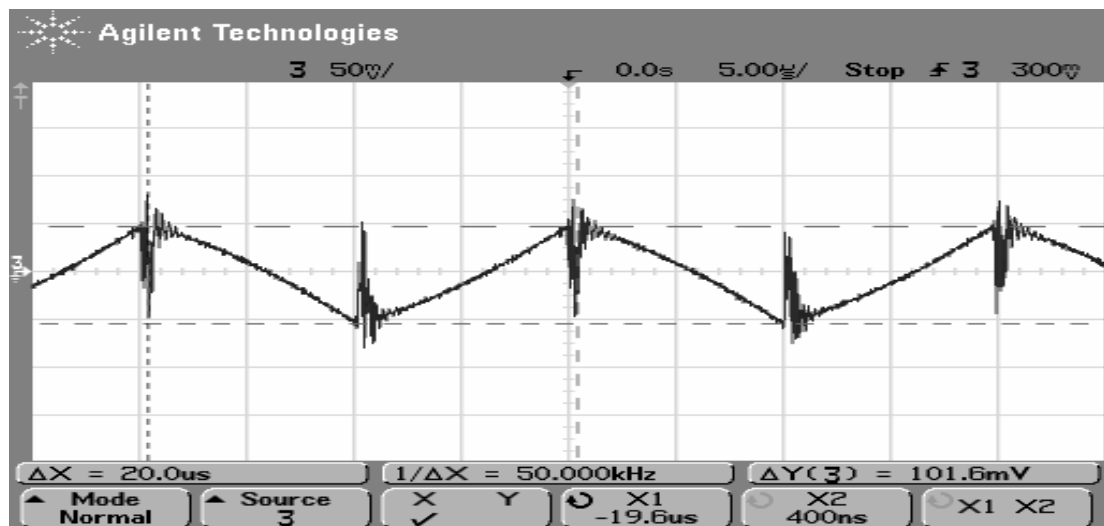


Figure 50 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).

The following results were obtained;

- Simulation result: Output voltage ripple is equal to 100 mV peak-to-peak AC.
- Measurement result: Output voltage is equal to 101.6 mV peak-to-peak AC.

It is seen that a great change occurs in the output voltage ripple value. This is due to the frequency increasement.

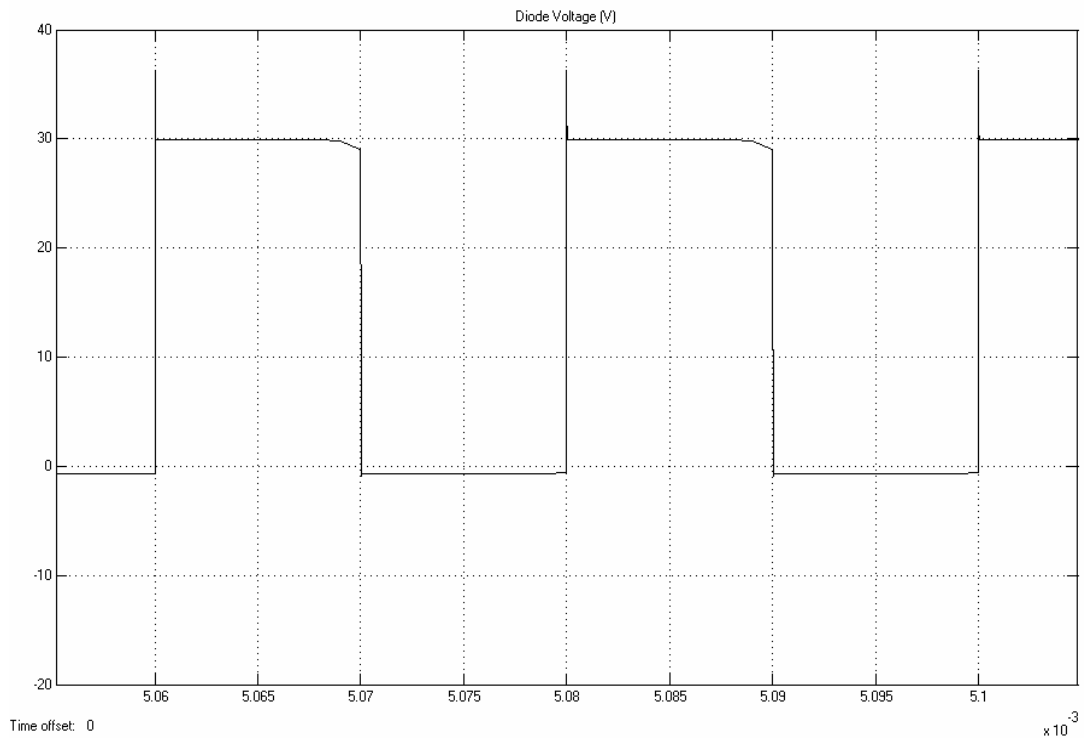


Figure 51 Simulation result-Buck converter diode voltage.

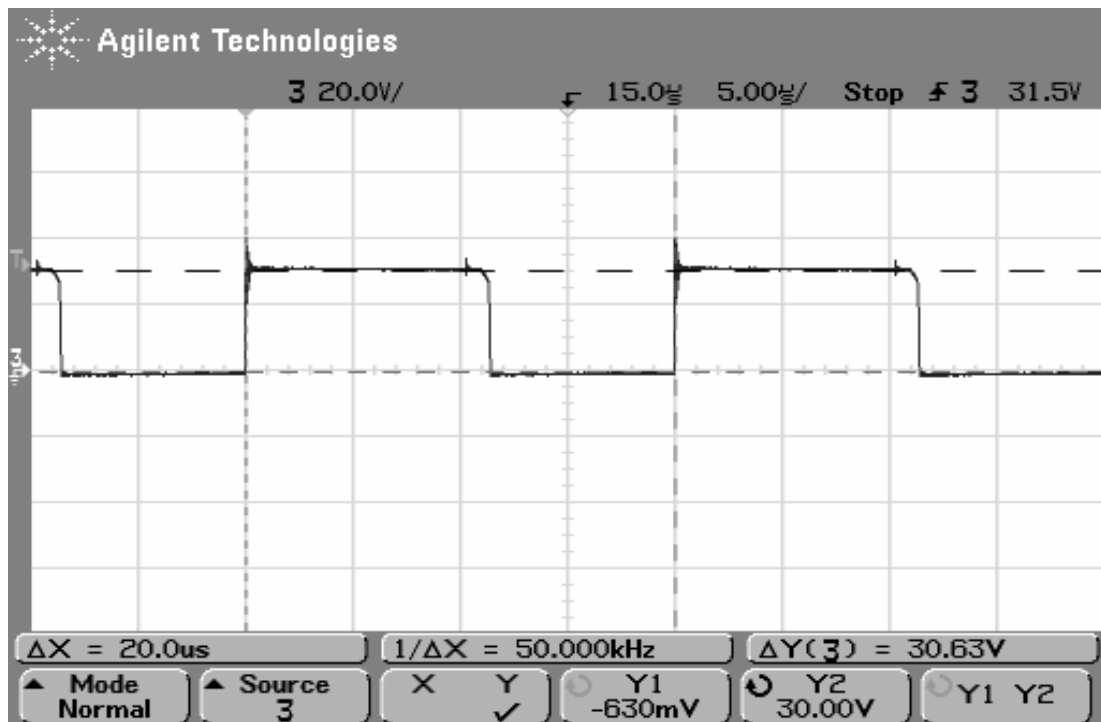


Figure 52 Measurement result-Buck converter diode voltage.

The following results are obtained:

- Simulation result: Diode voltage is equal to 30 V at diode off-state and to -630 mV (diode on-state voltage drop) at diode on-state.
- Measurement result: Diode voltage is equal to 30 V at diode off-state and to -630 mV (diode on-state voltage drop) at diode on-state.

Continuity can be also observed from diode voltage waveform. At continuous mode operation, the diode current does not reach to zero before switching period is terminated. This means that the diode voltage oscillation does not occur until the switching period is completed.

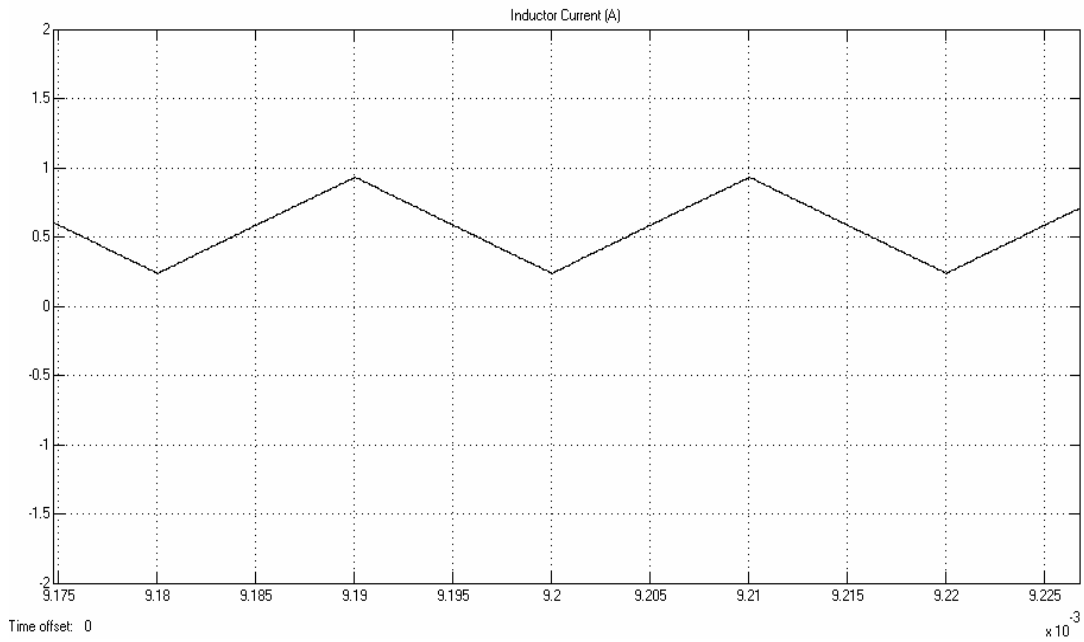


Figure 53 Simulation result-Buck converter inductor current.

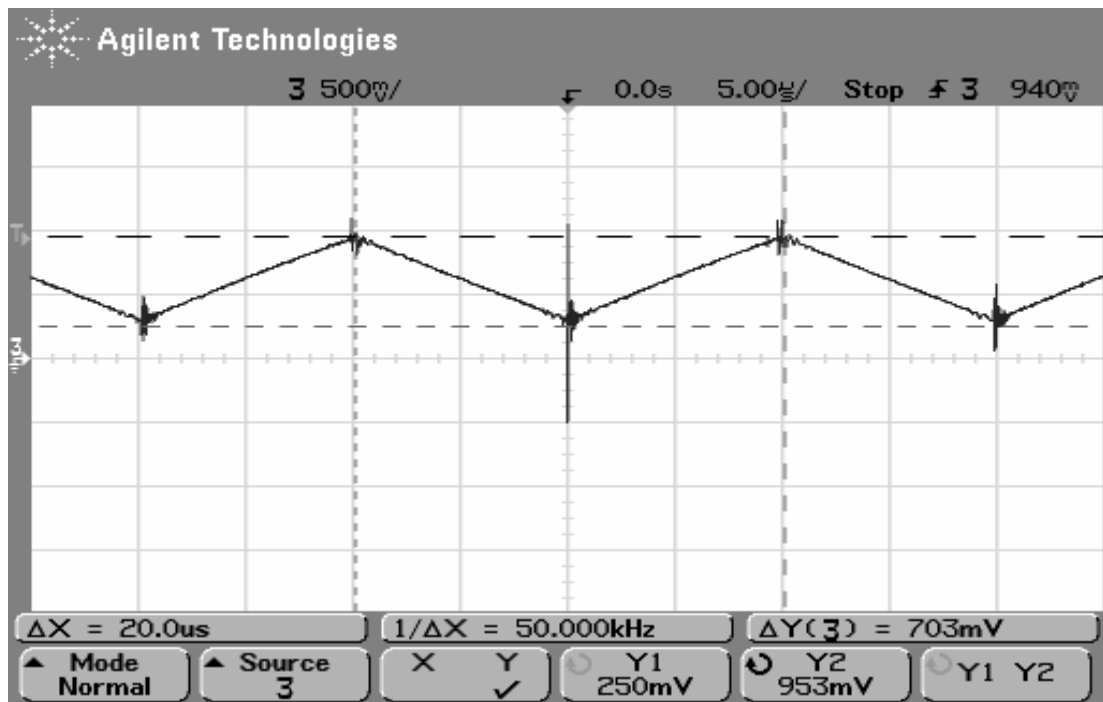


Figure 54 Measurement result-Buck converter inductor current.

The following results are obtained:

- Simulation result: Inductor current ripple is equal to 700 mA
- Measurement result: Inductor current ripple is equal to 703 A

It is known that the converter operates in CCM. Positive inductor current values during the switching period verify CCM operation.

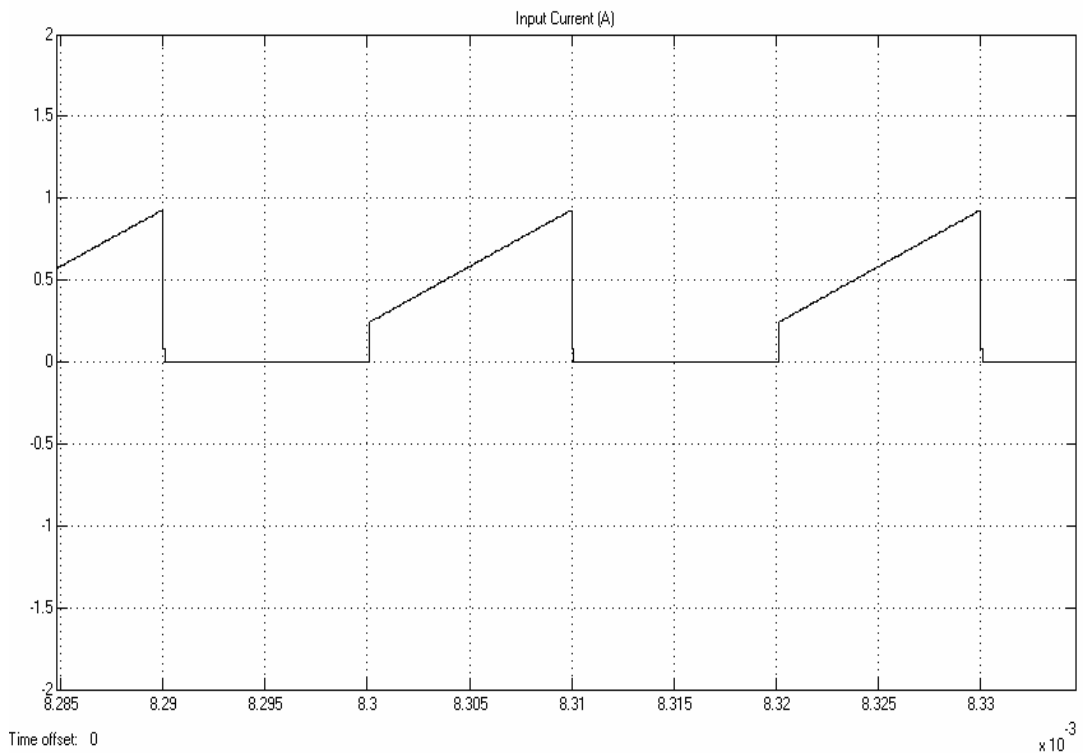


Figure 55 Simulation result-Buck converter input current.

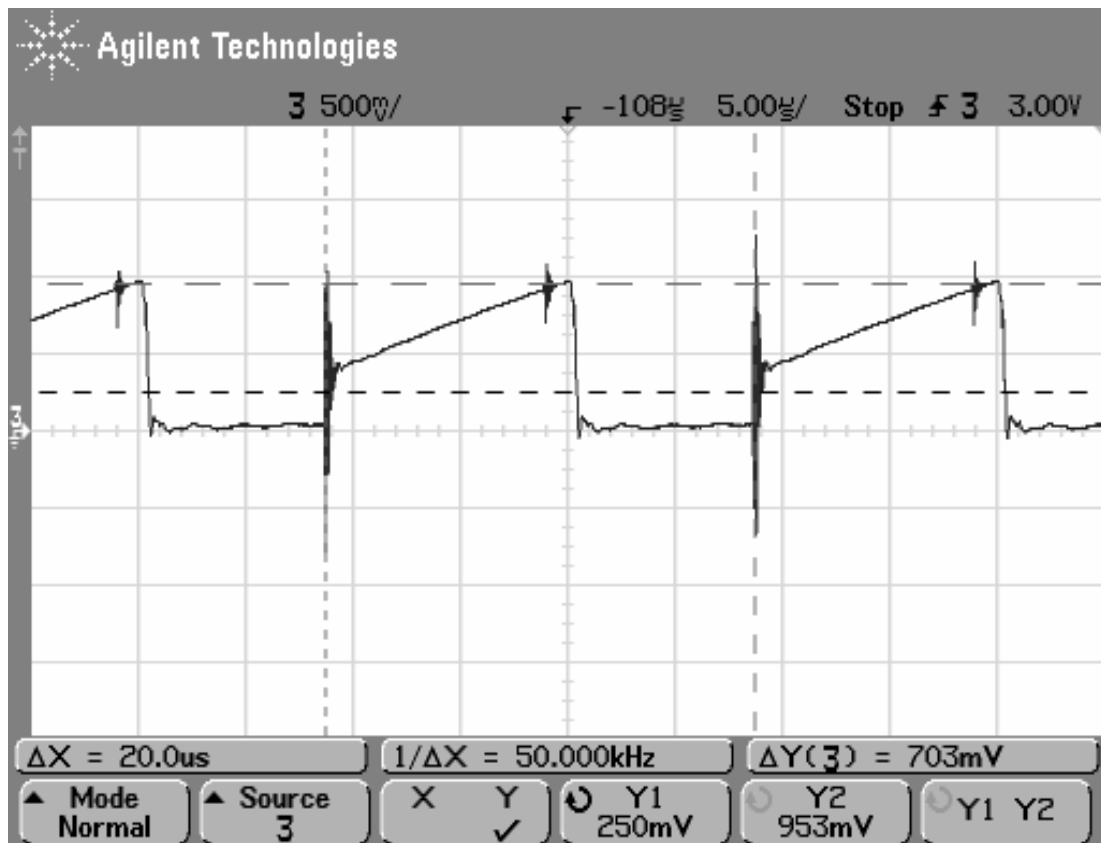


Figure 56 Measurement result-Buck converter input current.

The following results are obtained:

- Simulation result: Input current ripple is equal to 700 mA.
- Measurement result: Input current ripple is equal to 703 mA.

It is known that the converter operates in CCM. Positive input current values when switch is turned-on verify CCM operation.

The followings are the other waveforms. Continuity will be also observed on these waveforms.

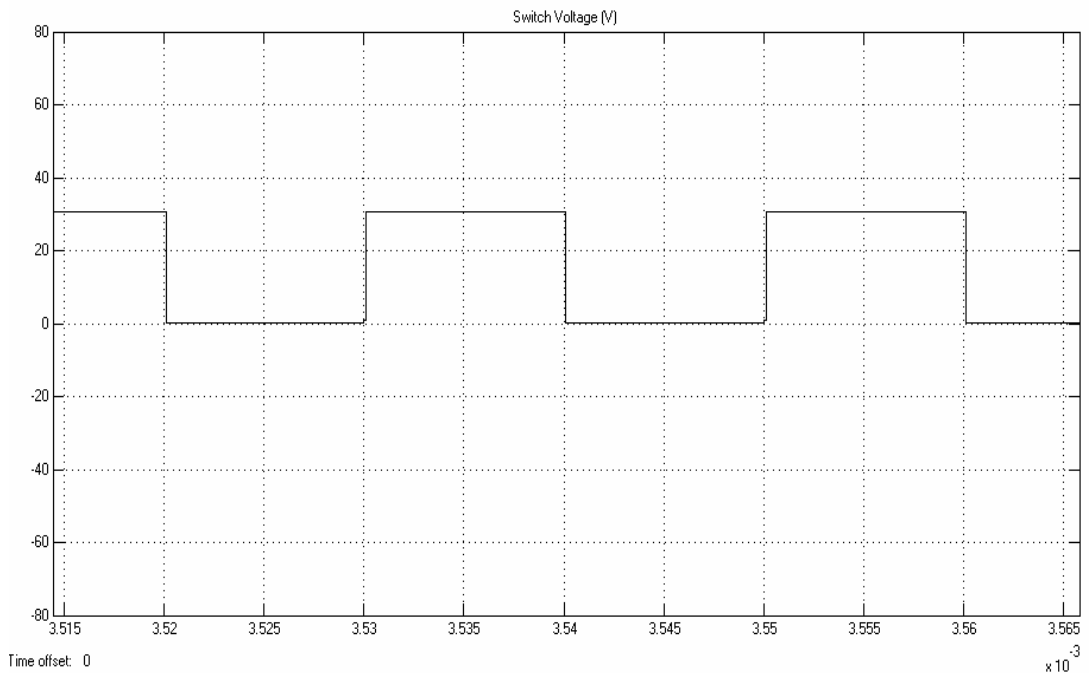


Figure 57 Simulation result-Buck converter switch voltage.

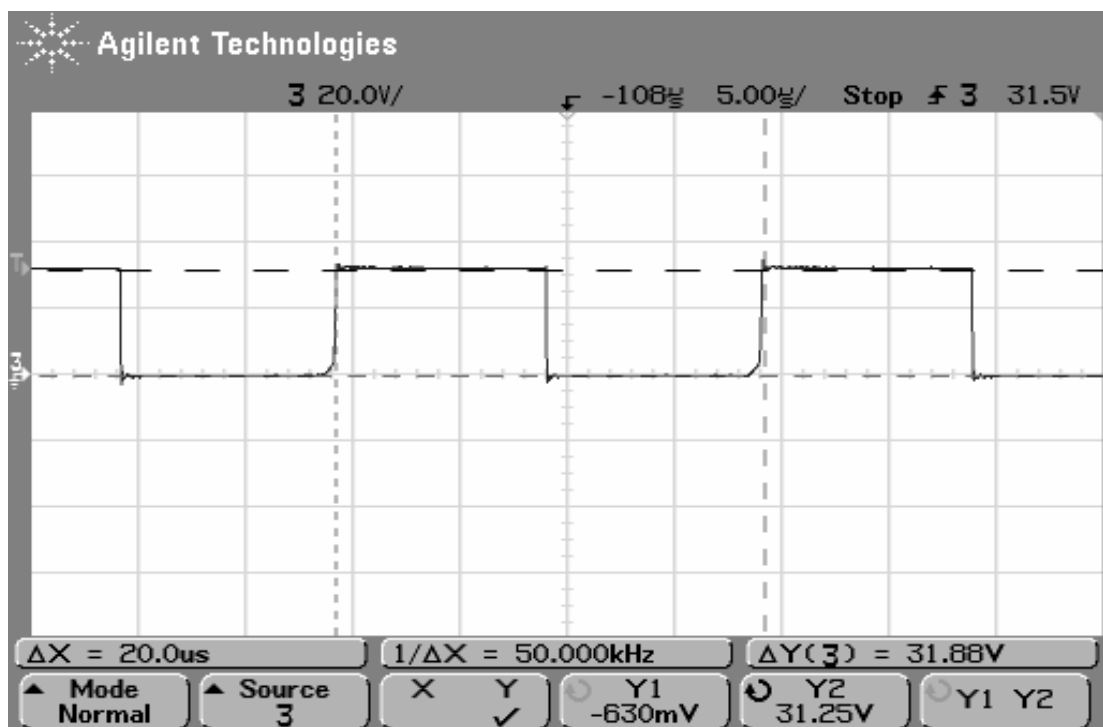


Figure 58 Measurement result-Buck converter switch voltage.

The following results are obtained:

- Simulation result: Switch voltage is equal to 30 V at switch off-state and to -630 mV (switch on-state voltage drop) at switch on-state.
- Measurement result: Switch voltage is equal to 31.25 V at switch off-state and to -630 mV (switch on-state voltage drop) at switch on-state.

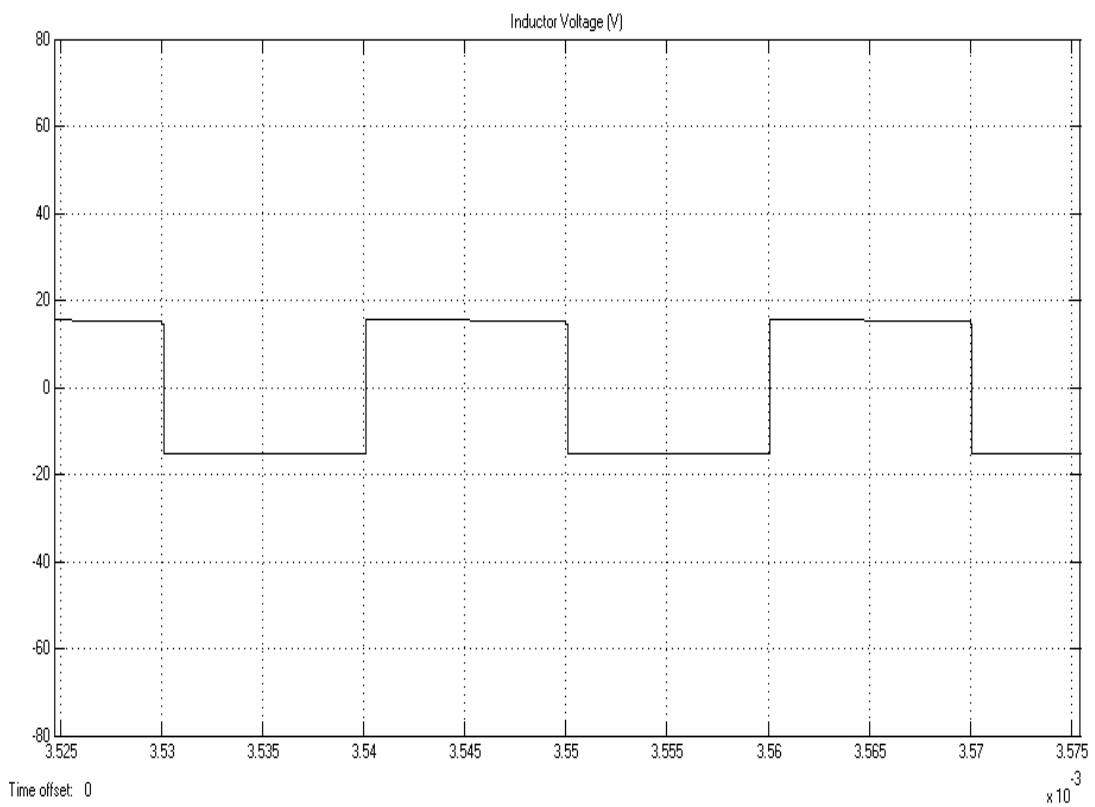


Figure 59 Simulation result-Buck converter inductor voltage.

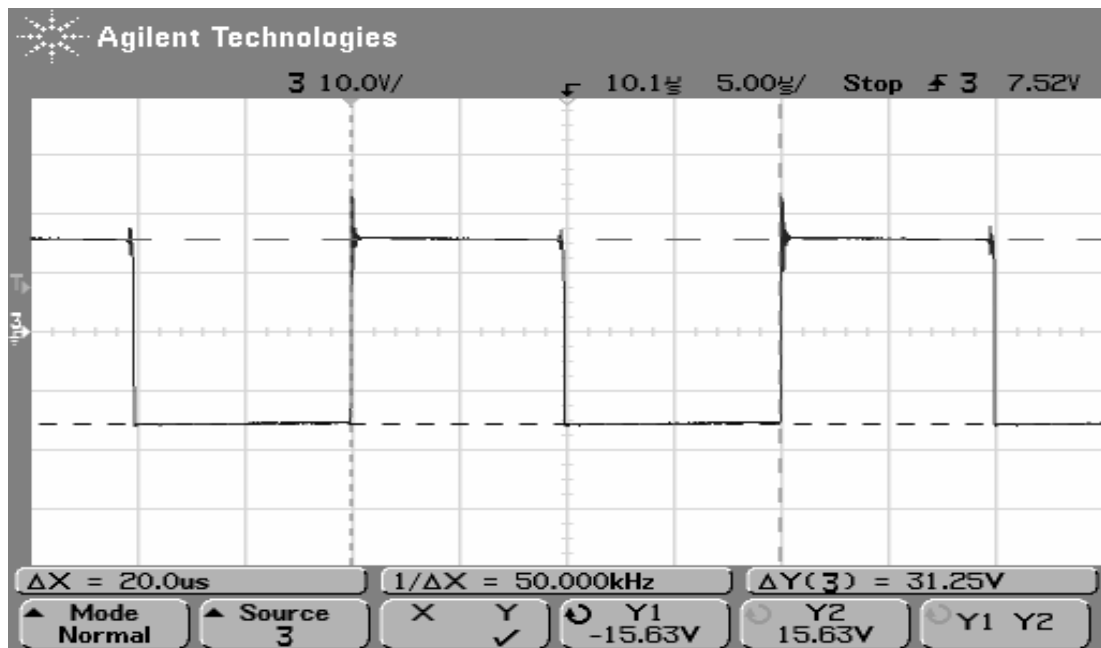


Figure 60 Measurement result-Buck converter inductor voltage.

The following results are obtained:

- Simulation result: Inductor voltage is equal to 15.4 V at switch off-state and to -15.4 V at switch on-state.
- Measurement result: Inductor voltage is equal to 15.63 V at switch off-state and to -15.63 V at switch on-state.

The following steps are related with the closed loop control of the converter.

Step-19: The following design inputs are entered:

- $V_{in} = 30 \text{ V}$
- $V_o = 15 \text{ V}$
- $R = 7 \Omega$
- $f_s = 20000 \text{ Hz}$
- $C = 100 \mu\text{F}$
- $L = 220 \mu\text{H}$

Step-20: “Design” button is pressed. The following design outputs are obtained:

- Output Power = 32.14 W
- Duty Cycle = 50 %
- Minimum Load for DCM = 17.6 Ω
- Output Voltage Ripple = 213 mV
- Inductor Current Ripple = 1.7 A

Step-21: “Continuity Check” button is pressed and it is seen that the designed converter operates in CCM (continuous conduction mode).

Step-22: “Frequency Response” button is pressed in “Small-Signal Model (G_{vd})” section and the followings are observed (Figure 61);

- Phase Margin = $180^\circ - 178^\circ = 2^\circ$
- Cut-off Frequency = 5930 Hz

After finishing the application, the converter transfer function (G_{vd}) is observed by typing “ G_{vd} ” on MATLAB Workspace as shown below:

```
>> Gvd

Transfer function:
      1.364e009
-----
s^2 + 1429 s + 4.545e007
```

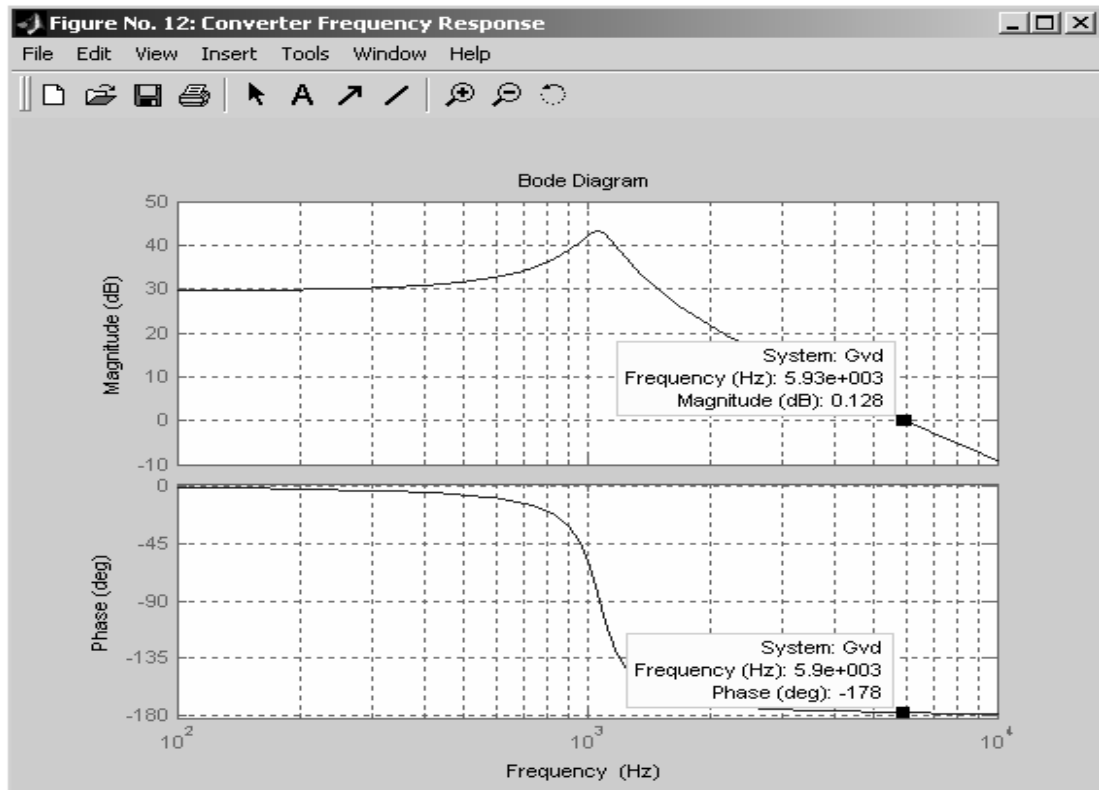



Figure 61 Frequency response of “Small-Signal Model (G_{vd})”.

Step-23: “Poles/Zeroes” button in “Small-Signal Model (G_{vd})” section is pressed and it is seen that the converter transfer function has two poles that are equal to:

- $p_1 = -714 + 6704i$
- $p_2 = -714 - 6704i$

“Small-Signal Model (G_{vd})” has no zeros.

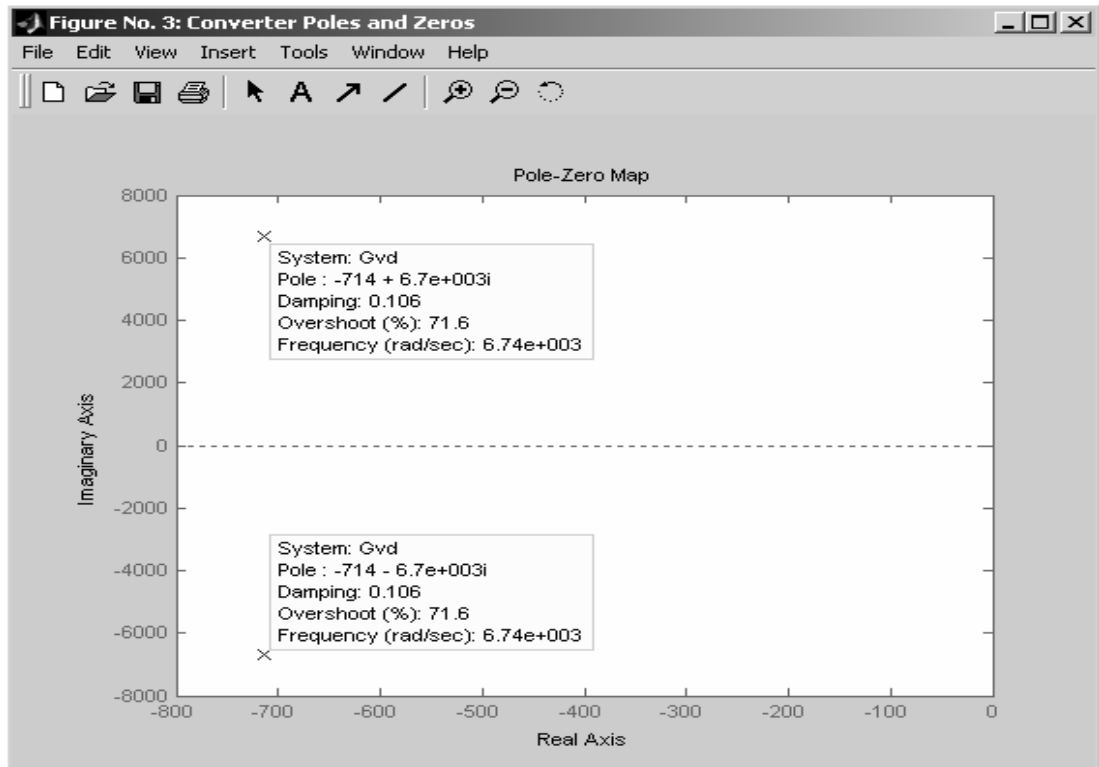


Figure 62 Poles and zeroes of “Small-Signal Model (G_{vd}).

Step-24: Amplitude of the sawtooth signal “ V_m ” and feedback gain “ H ” in the “Uncompensated Loop (T_u)” section are entered then “Set Model” button is pressed.

- $V_m = 5$
- $H = 0.166$

Step-25: “Frequency Response” button is pressed in “Uncompensated Loop (T_u)” section and the followings are obtained;

- Phase Margin = $180^\circ - 162^\circ = 18^\circ$
- Cut-off Frequency = 9390 Hz

Low frequency components are needed to be improved in order to take compensated-loop transfer function “T” as high as possible, A PI compensator is used to obtain this design criteria.

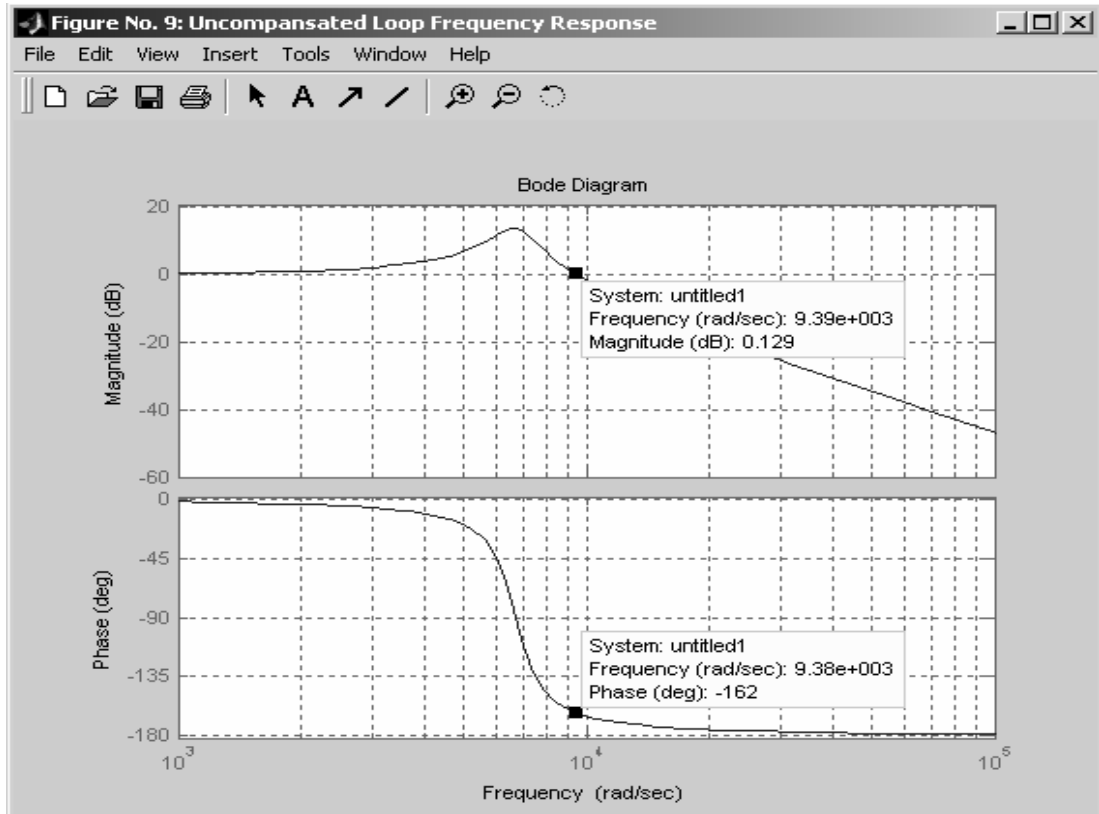


Figure 63 Frequency Response of “Uncompensated Loop (T_u)”.

After finishing the application, the uncompensated closed loop transfer function (T_u) is observed by typing “ T_u ” on MATLAB Workspace as shown below:

```
>> Tu

Transfer function:
    4.527e007
-----
s^2 + 1429 s + 4.545e007
```

Step-26: “Poles/Zeroes” button is pressed in “Uncompensated Loop (T_u)” section and the following figure is observed (Figure 64):

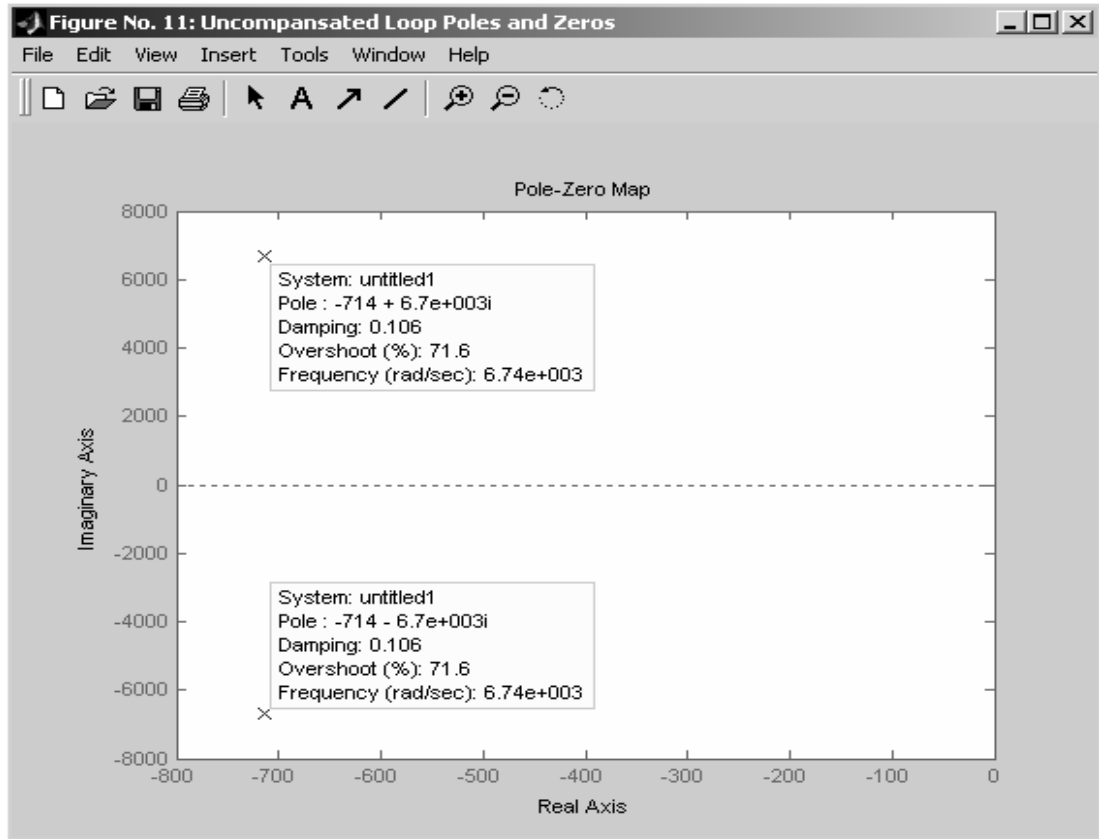


Figure 64 Poles and zeroes of “Uncompensated Loop (T_u)”.

It is seen that the uncompensated converter transfer function has two poles that are;

- $p_1 = -714 + 6704i$
- $p_2 = -714 - 6704i$

which are 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 ” constant.

Step-27: The proportional gain “ K_p ” and the integral gain “ K_i ” given below are entered in the “Compensated Loop (T)” section, then “Set Model” button is pressed.

- $K_p = 2.039$
- $K_i = 618.5$

Step-28: The cut-off frequency and phase margin are automatically calculated as given below,

- PM (phase margin) = 8.916°
- f_c (cut-off frequency) = 1857.95 Hz

After finishing the application, the PI compensator is observed by typing “ T_u ” on MATLAB Workspace as shown below:

```
>> PI

Transfer function:
2.039 s + 618.5
-----
      s
```

The related PI compensator frequency response is observed by typing “`bode(PI)`” on the workspace as shown below (Figure 65):

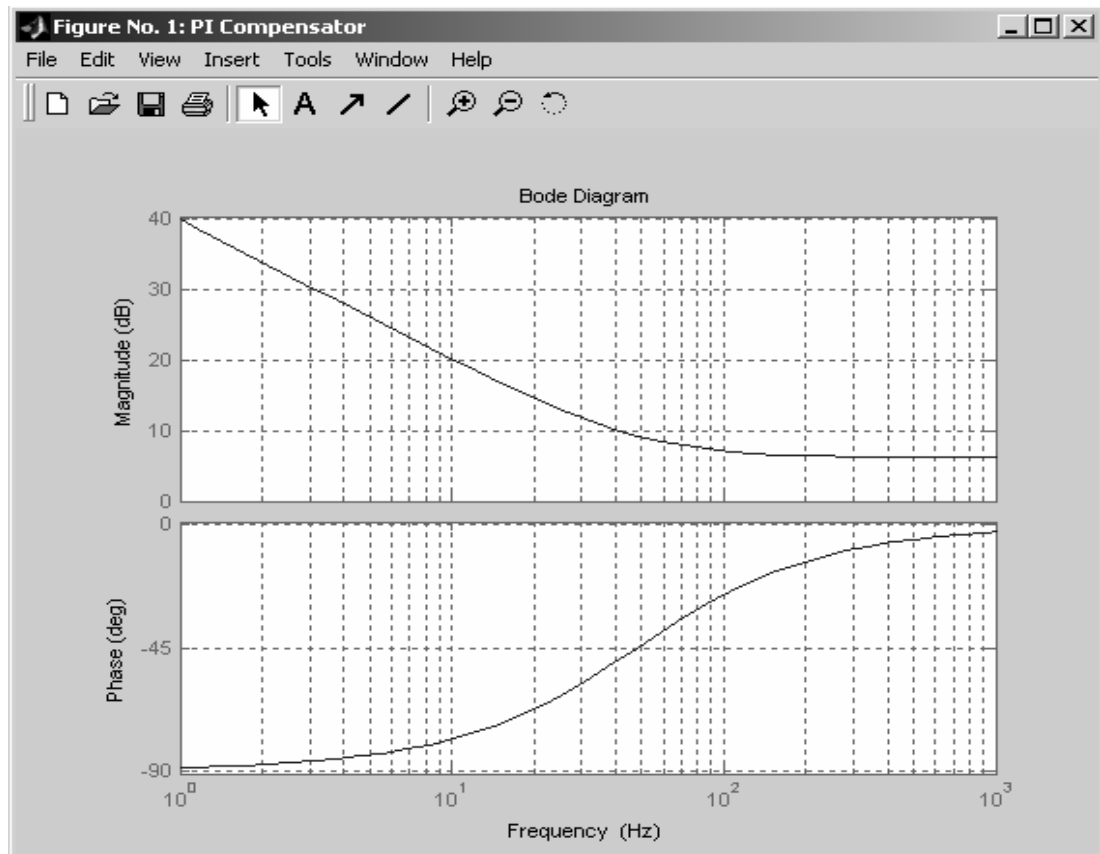


Figure 65 PI compensator frequency response.

Another figure named “Closed Loop Time Response” is plotted when “Set Model” button is pressed on this section. This figure shows how the time response of the closed loop transfer function changes in accordance with the selected phase margin. It is known that when the phase margin is increased, oscillations will also increase on the output (underdamped) and when phase margin is decreased, oscillations will also decrease (overdamped). The user can observe the time response characteristics of different closed loop models with different K_p and K_i values by pressing “Re-Design” button on the bottom of this section. All the time response characteristics are on a single plot that provides to make comparison.

The related closed loop time response is given Figure 66. This figure consists of two components; first is the input reference signal, the second is the related output with no ripple. It must be remembered that the small-signal approximation is used to

generate all the transfer functions upto now, which neglects the high frequency AC ripples. So, this figure does not represent the real output characteristic on time, but gives the user an idea about the response time of the designed closed-loop model.

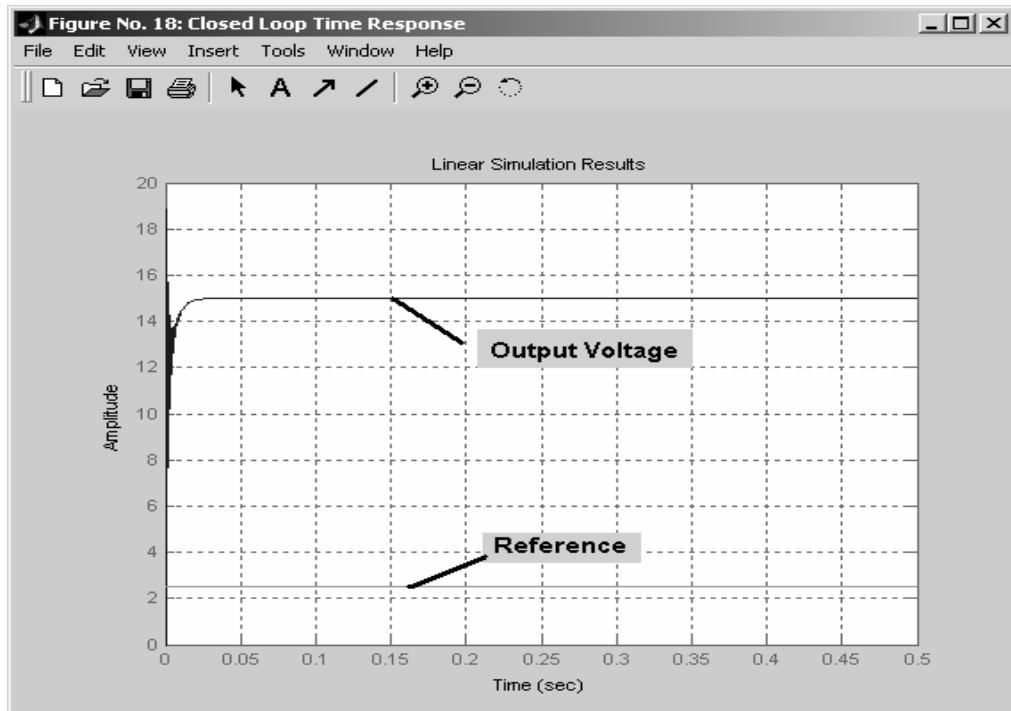


Figure 66 Closed loop (reference-to-output) transfer function time response.

Step-29: “Frequency Response” button is pressed in “Compensated Loop (T)” window and the following figure is observed (Figure 67).

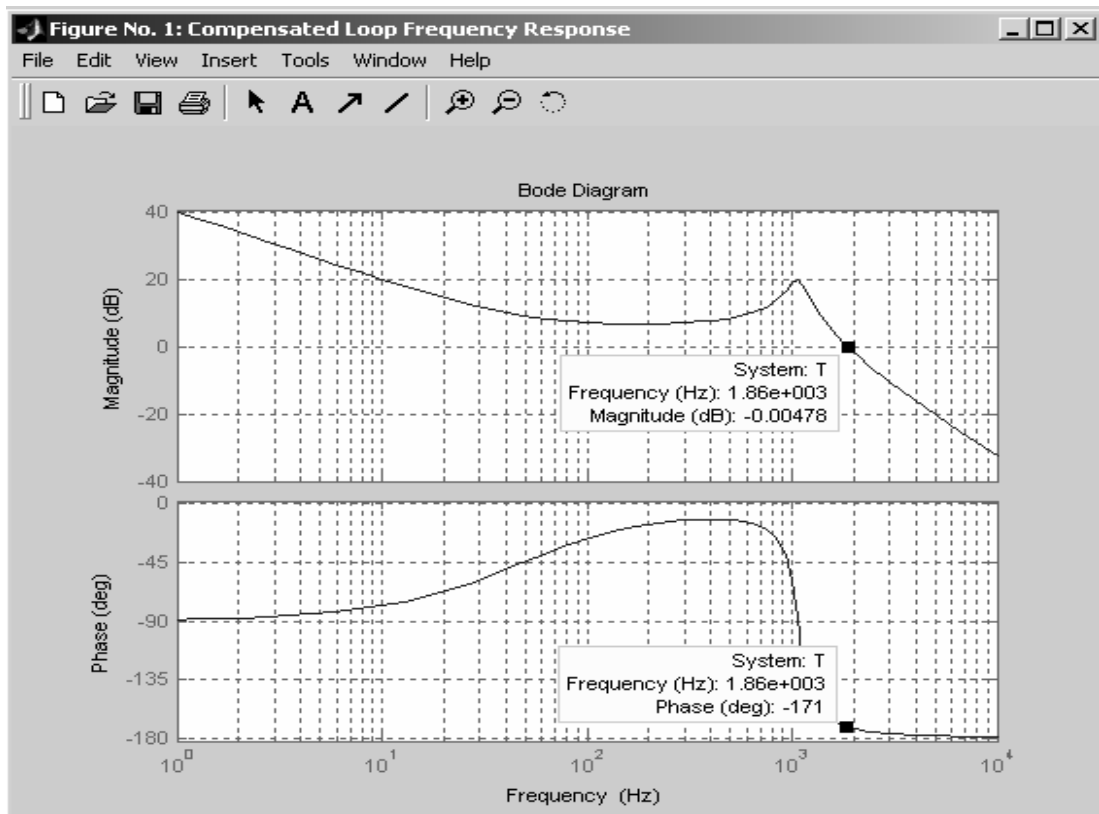


Figure 67 Frequency Response of “Compensated Loop (T)”.

It is seen that the compensated loop transfer function has:

- Phase Margin = $180^\circ - 171^\circ = 9^\circ$
- Cut-off Frequency = 1860 Hz

After finishing the application, compensated closed loop transfer function (T) is observed by typing “T” on MATLAB Workspace as shown below:

```
>> T

Transfer function:
  9.231e007 s + 2.8e010
-----
s^3 + 1429 s^2 + 4.545e007 s
```

Step-30: “Poles/Zeros” button is pressed in “Compensated Loop (T)” section and the following figure is obtained (Figure 68):

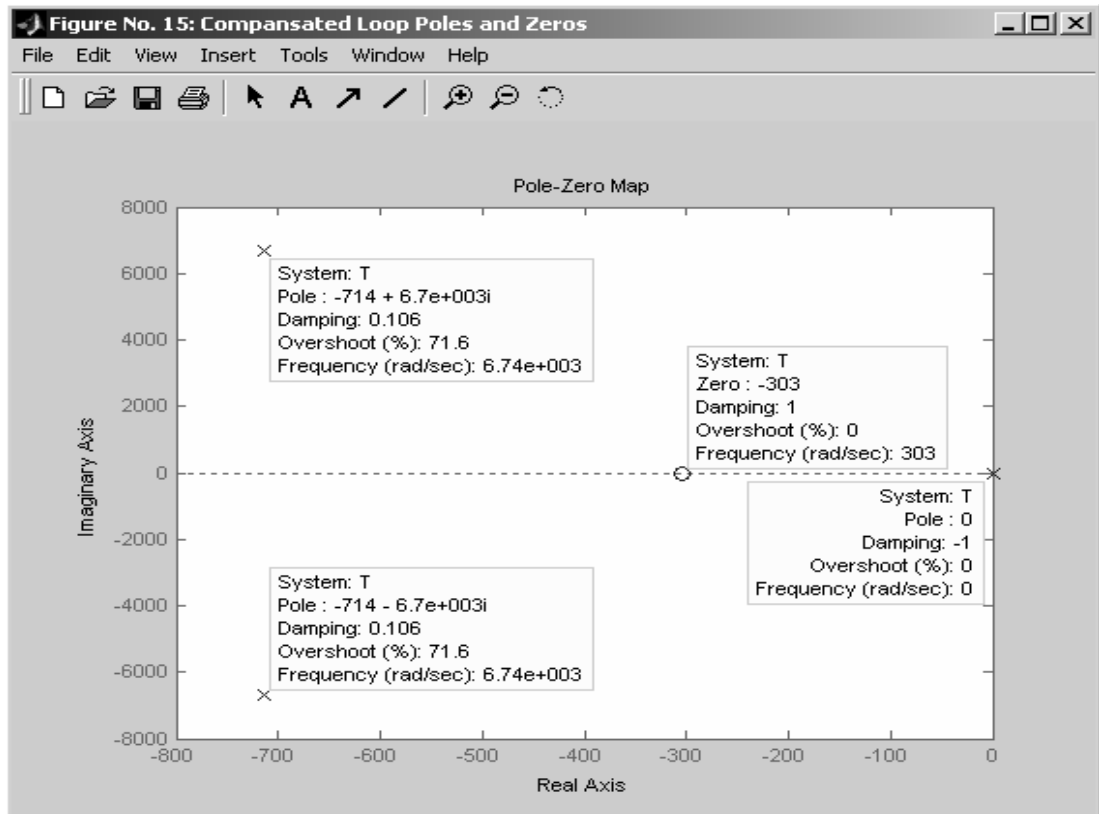


Figure 68 Poles and Zeroes of “Compensated Loop (T)”.

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

- $p_1 = -714 + 6704i$
- $p_2 = -714 - 6704i$
- $p_3 = 0$
- $z_1 = -303$

where p_1, p_2 are same as the uncompensated closed-loop transfer function “ T_u ”. The other zero and pole are added by the PI compensator.

Stability analysis can be performed by observing the poles (whether positive or negative) of the compensated closed-loop model. If any of the poles is positive (or in Right-Hand-Plane (RHP)), then the system is unstable. For stability, all of the

poles of the compensated closed-loop should be negative (or in Left-Hand-Plane (LHP)). So, the designed system is stable.

When the “Frequency Response” button is pressed, the “Design Summary” figure shows “ G_{vd} ”, “ T_u ” and “ T ”. Bode diagrams on the same plot as indicated below (Figure 69).

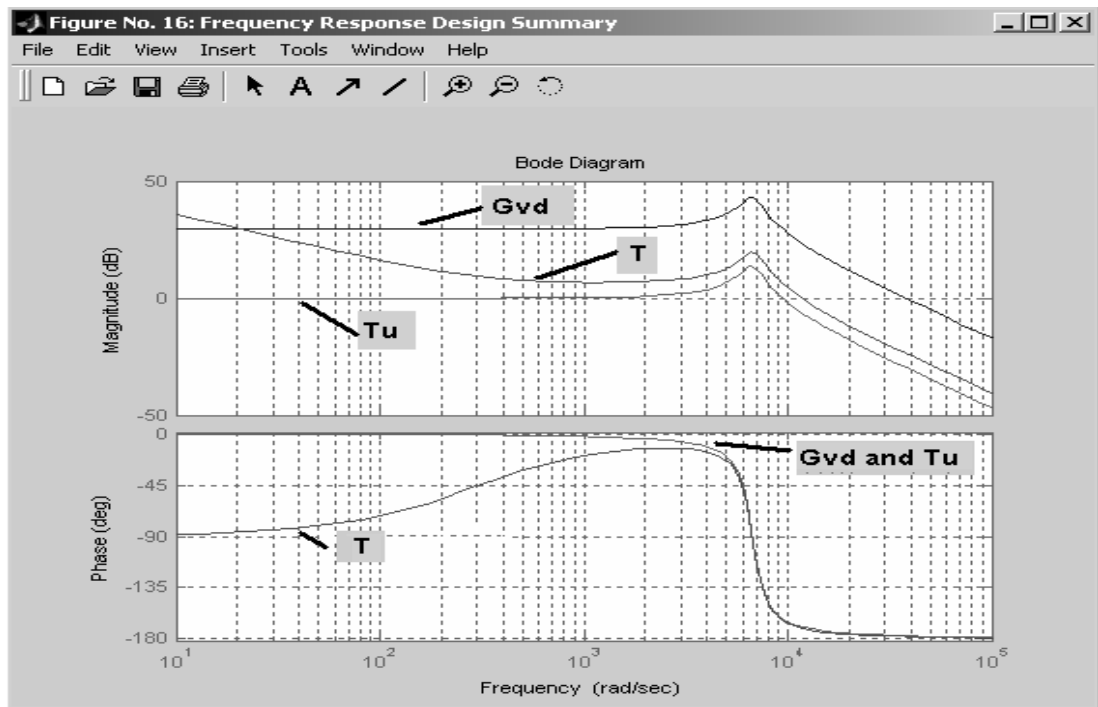


Figure 69 “Frequency Response Design Summary” at the end of design.

Step-31: “Auto Settings” button is pressed to set the simulation. It is seen that the “Simulation Parameters” section is automatically filled with pre-determined design values.

Step-32: “Manual Settings” button is pressed to set the reference change time and value. The following settings are entered on “Converter Design” GUI:

Table 3 Closed loop simulation parameters (reference change)

Reference Change	Final Reference: 0 V	Change Time: 0.03 s
Load Regulation	Final Load: 25 Ω	Change Time: 0.06 s
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.06 s
Line Regulation (AC)	Amplitude: 2 V peak; Frequency: 50 Hz	Change Time: 0.06 s

Step-33: “Closed Loop Simulation” button is pressed to start the simulation. At the same time, real measurements are also taken by using an oscilloscope. The followings are simulation and measurement results.

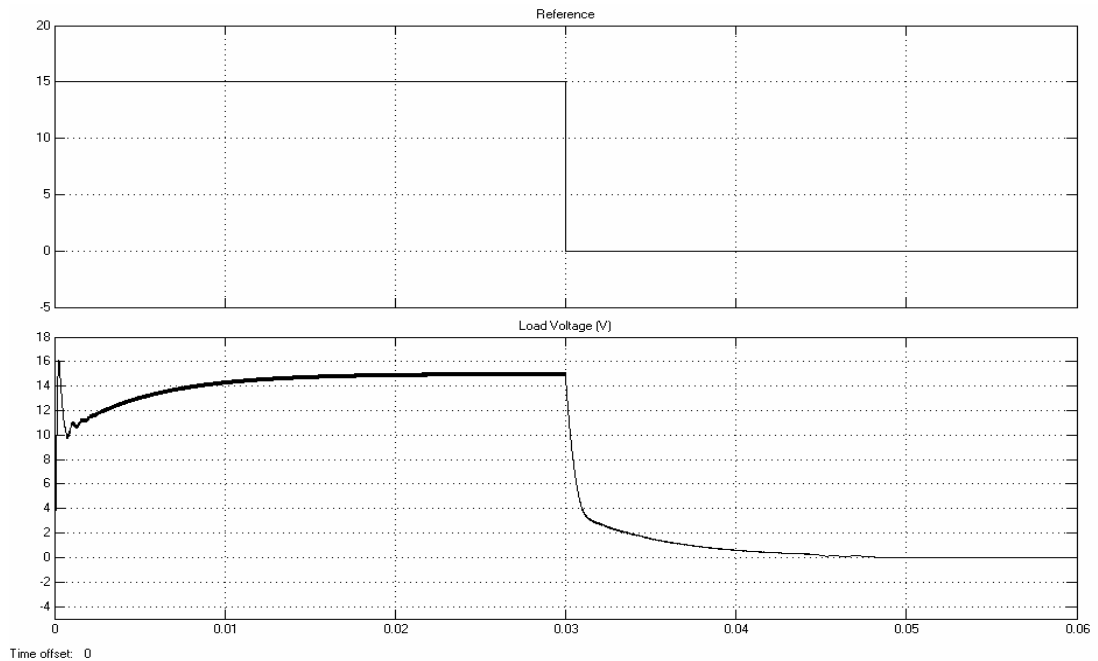


Figure 70 Simulation result-Buck converter output voltage at reference change (at t = 0 s, reference is setting from 0 V to 15 V and at t = 0.03 s, reference is setting from 15 V to 0 V).

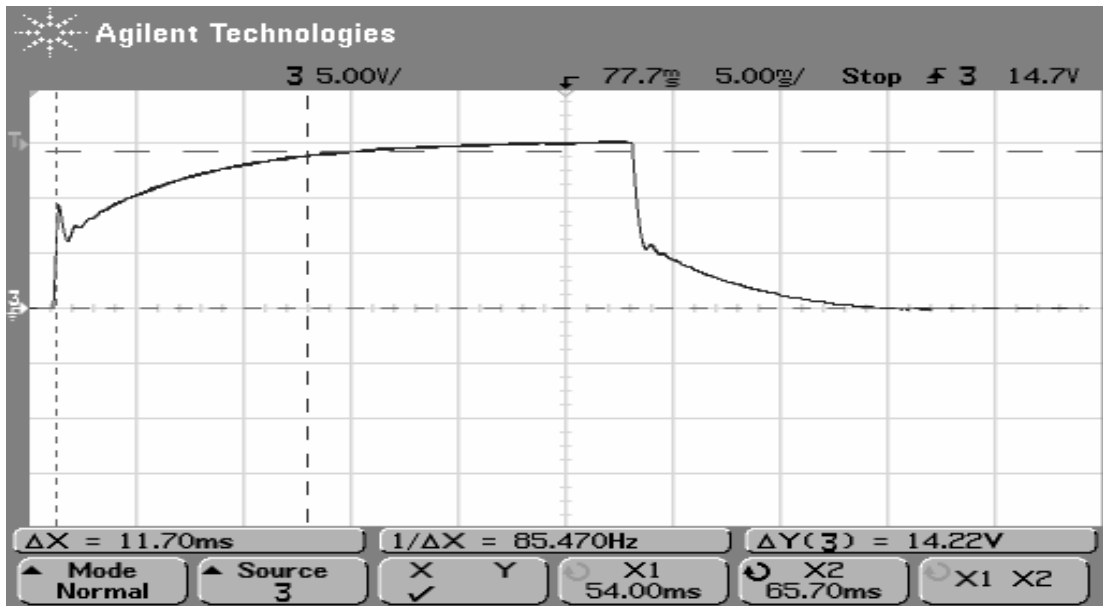


Figure 71 Measurement result-Buck converter output voltage at reference change (at $t = 0.03$ s, reference is setting from 0 V to 15 V).

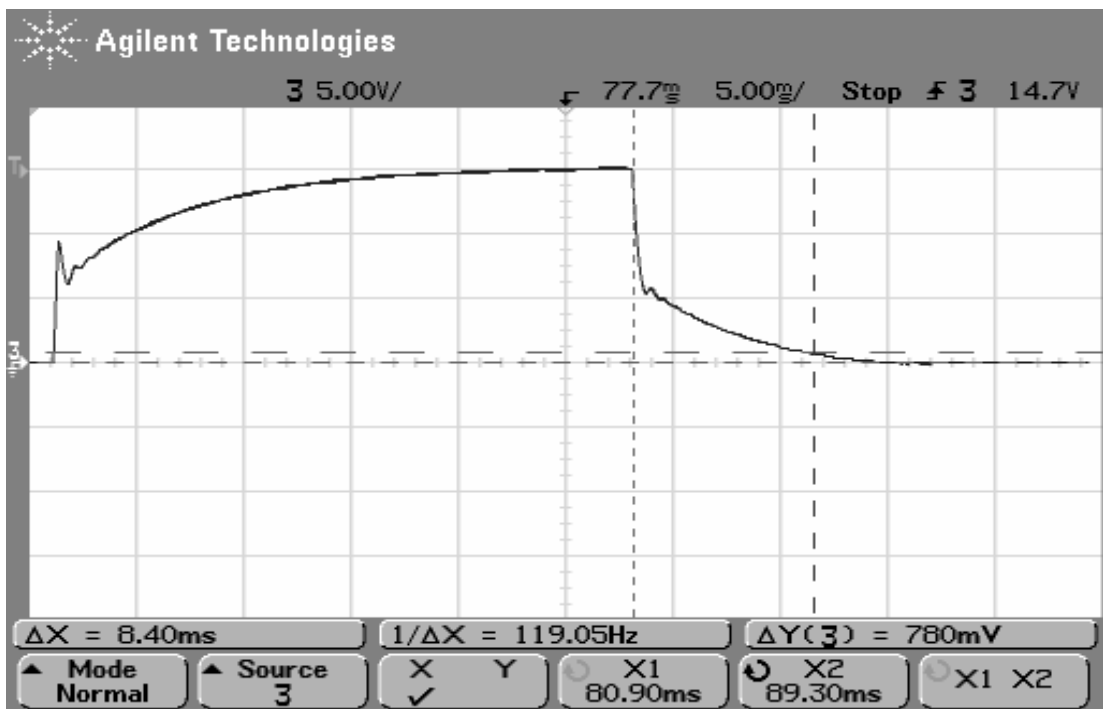


Figure 72 Measurement result-Buck converter output voltage at reference change (at $t = 0.03$ s, reference is setting from 15 V to 0 V).

The following results are obtained;

- Simulation result: Settling time when the reference is changed from 0 to 15 at $t = 0$ second is equal to 10 ms and the settling time when the reference is changed from 15 to 0 at $t = 0.03$ second is equal to 8.5 ms.
- Measurement result: Settling time when the reference is changed from 0 to 15 at $t = 0$ second is equal to 11.7 ms and the settling time when the reference is changed from 15 to 0 at $t = 0.03$ second is equal to 8.4 ms

It is seen that the designed and applied compensator provides the needed output in a reference change case.

Step-34: “Manual Settings” button is pressed to set the load commutation time and value. The following settings are entered on “Converter Design” GUI:

Table 4 Closed loop simulation parameters (load change)

Reference Change	Final Reference: 0 V	Change Time: 0.06 s
Load Regulation	Final Load: 25 Ω	Change Time: 0.03 s
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.06 s
Line Regulation (AC)	Amplitude: 2 V peak ; Frequency: 50 Hz	Change Time: 0.06 s

Step-35: “Closed Loop Simulation” button is pressed to start the simulation. At the same time, real measurements are also taken by using an oscilloscope. The followings are simulation and measurement results.

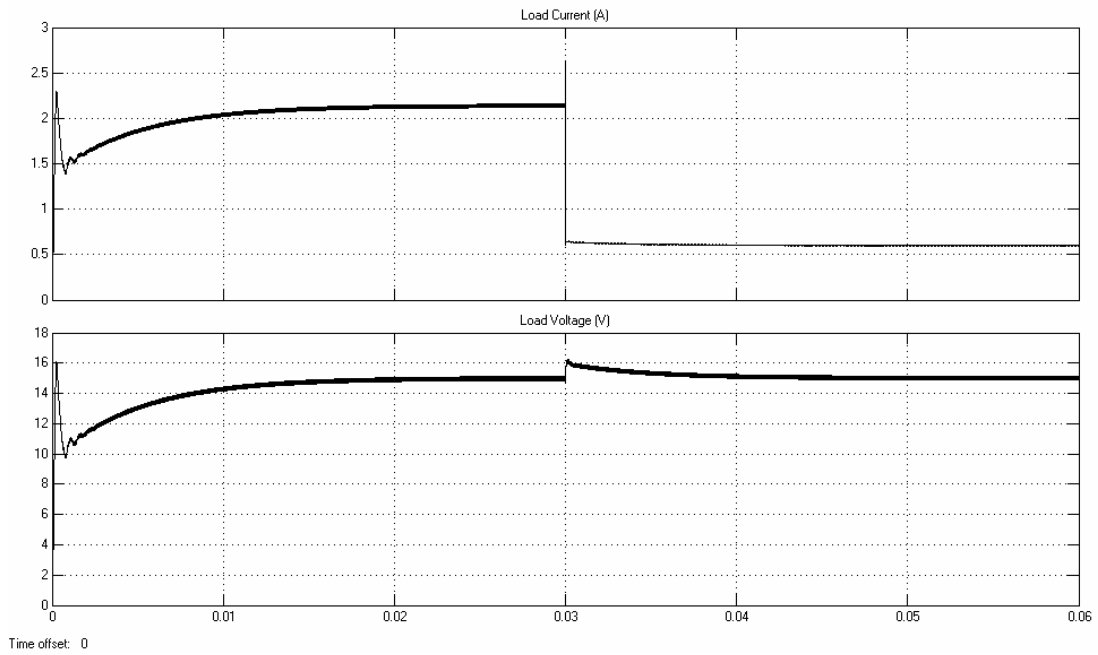


Figure 73 Simulation result-Buck converter load characteristics at load change (at $t = 0.03$ s, load is changed from 7Ω to 25Ω).

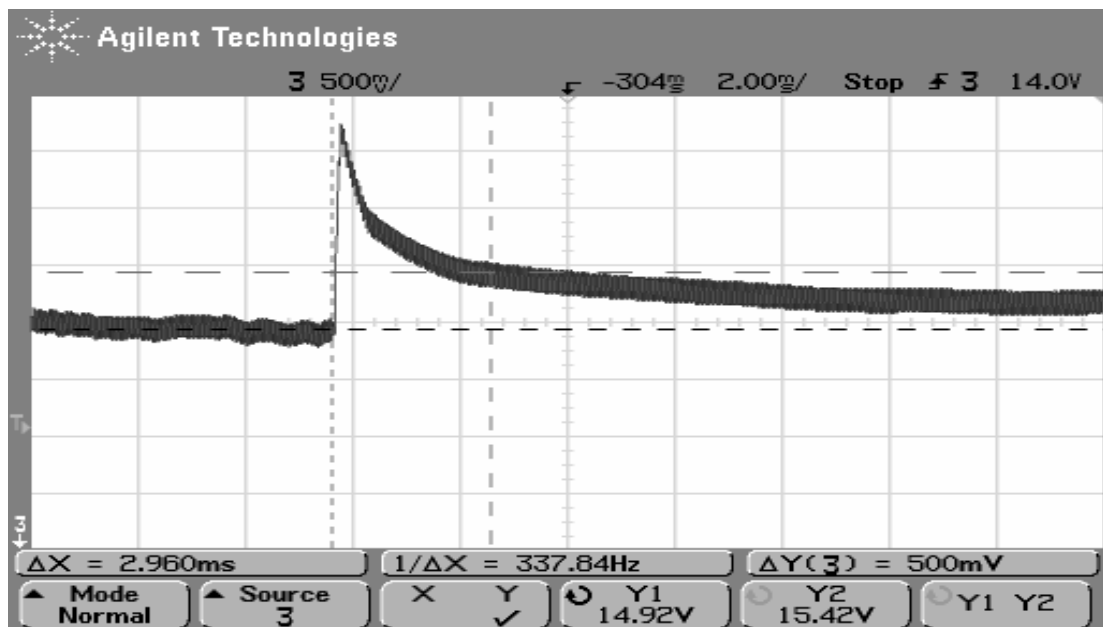


Figure 74 Measurement result-Buck converter output voltage at load change (at $t = 0.03$ s, load is changing from 7Ω to 25Ω).

The following results are obtained:

- Simulation result: Output voltage reaches to 15.5 V (when the load is changed from 7 Ω to 25 Ω at $t = 0.03$ s) is nearly equal to 3.2 ms.
- Measurement result: Output voltage reaches to 15.5 V (when the load is changed from 7 Ω to 25 Ω at $t = 0.03$ second) is nearly equal to 3 ms.

It is seen that the designed and applied compensator provides the needed output in a load change case.

Step-36: “Manual Settings” button is pressed to set the load commutation time and value. The following settings are entered on “Converter Design” GUI:

Table 5 Closed loop simulation parameters (DC line change)

Reference Change	Final Reference: 0V	Change Time: 0.06 s
Load Regulation	Final Load: 25 Ω	Change Time: 0.06 s
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.03 s
Line Regulation (AC)	Amplitude: 2.3 V peak; Frequency: 50 Hz	Change Time: 0.06 s

Step-37: “Closed Loop Simulation” button is pressed to start the simulation. At the same time, real measurements are also taken by using an oscilloscope. The followings are simulation and measurement results.

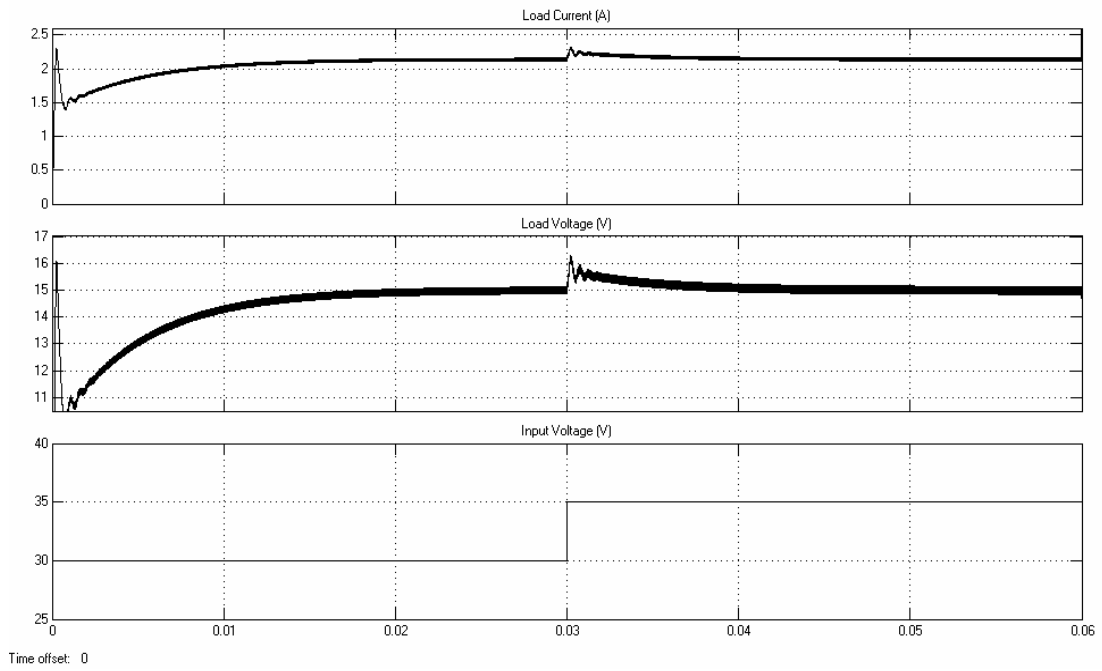


Figure 75 Simulation result-Buck converter load characteristics at DC line change (at $t = 0.03$ s, 5 V DC is added to the DC line input 30 V).

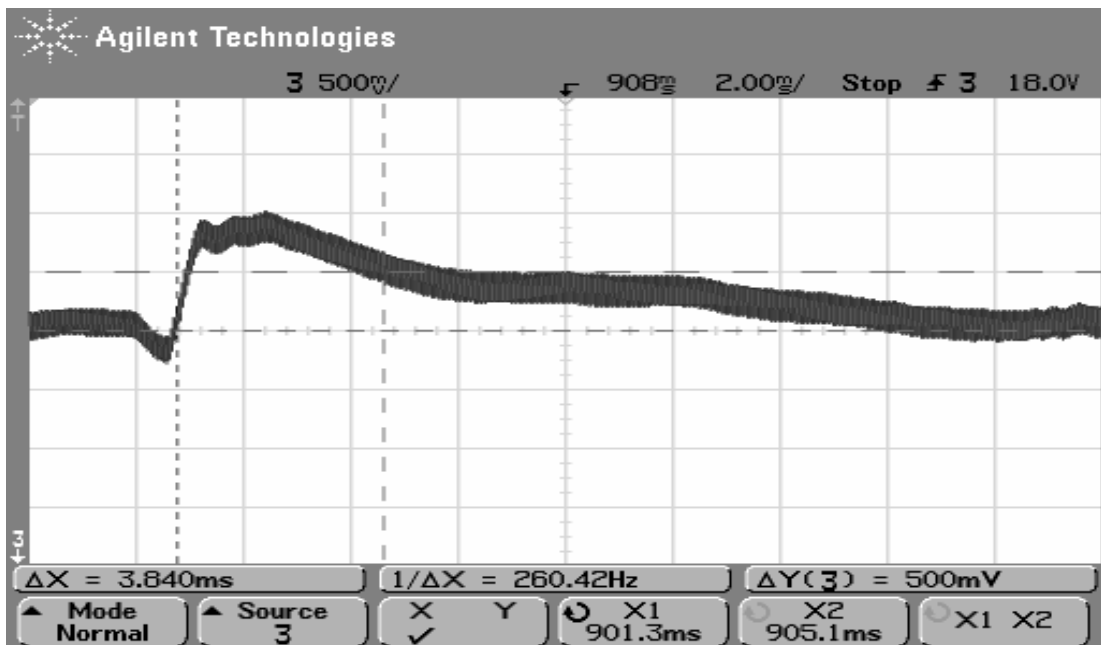


Figure 76 Measurement result-Buck converter load characteristics at DC line change (at $t = 0.03$ s, 5 V DC is added to the DC line input 30 V).

The following results are obtained;

- Simulation result: Output voltage reaches 15.5 V (when the DC line is changed from 30 V to 35 Ω at $t = 0.03$ s) is nearly equal to 3.3 ms.
- Measurement result: Output voltage reaches 15.5 V (when the DC line is changed from 30 V to 35 Ω at $t = 0.03$ second) is nearly equal to 3.84 ms.

It is seen that the designed and applied compensator provides the needed output in a DC line change case.

Step-38: “Manual Settings” button is pressed to set the load commutation time and value. The following settings are entered on “Converter Design” GUI:

Table 6 Closed loop simulation parameters (AC line change)

Reference Change	Final Reference: 0 V	Change Time: 0.06 s
Load Regulation	Final Load: 25 Ω	Change Time: 0.06 s
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.06 s
Line Regulation (AC)	Amplitude: 4.6 V peak; Frequency: 50 Hz	Change Time: 0.03 s

Step-39: “Closed Loop Simulation” button is pressed to start the simulation. At the same time, real measurements are also taken by using an oscilloscope. The followings are simulation and measurement results.

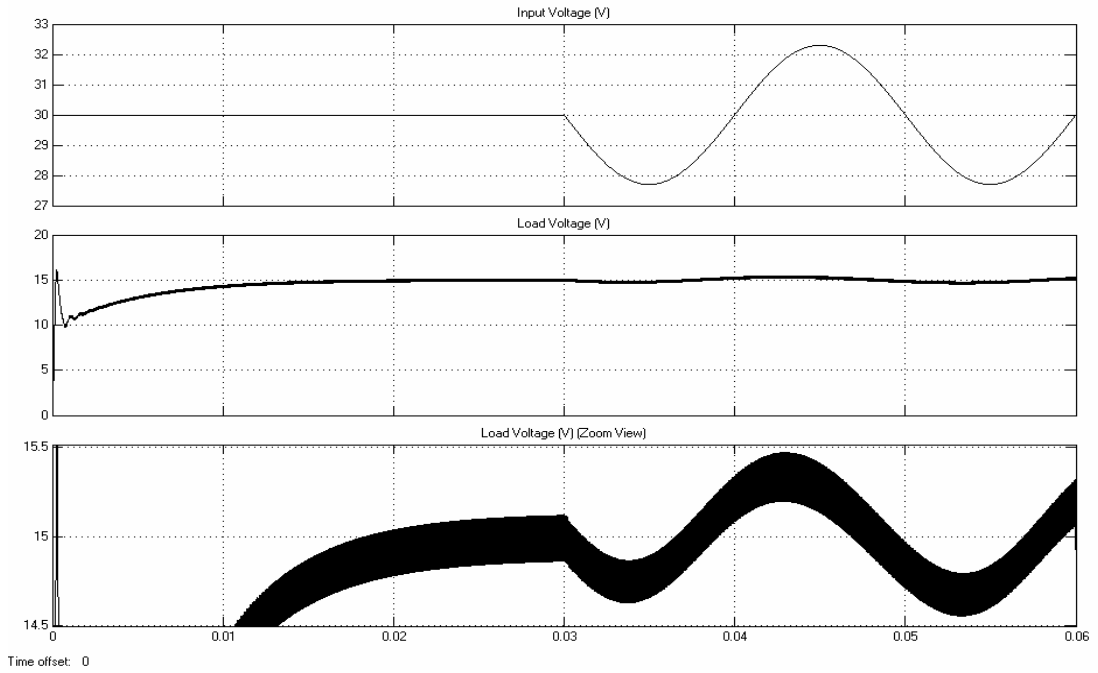


Figure 77 Simulation result-Buck converter load characteristics at AC line change (at $t = 0.03$ s, 4.6 V peak AC is added to the DC line input 30 V).

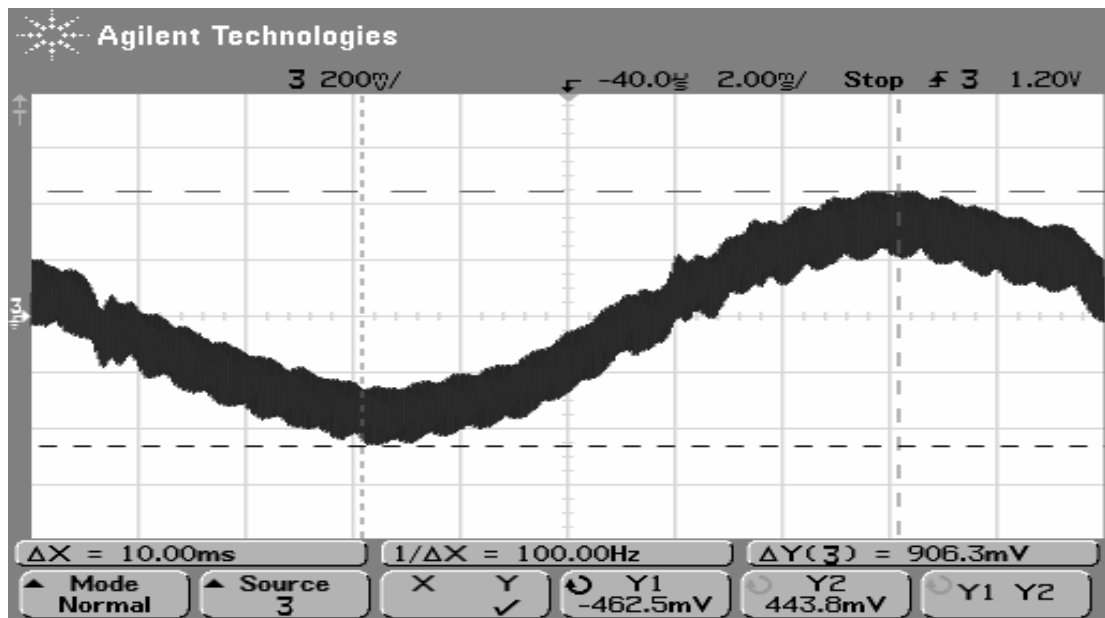


Figure 78 Measurement result-Buck converter output voltage at 4.6 V peak-to-peak AC line change (oscilloscope at AC Mode).

The following results are obtained:

- Simulation result: 4.6 V peak-to-peak AC line disturbances are compensated and reflected to the output as 950 mV peak-to-peak.
- Measurement result: 4.6 V peak-to-peak AC line disturbances are compensated and reflected to the output as 906.3 mV peak-to-peak.

It is seen that the designed and applied compensator provides the needed output in a AC line change case.

As a summary, the designed converter is verified by simulation and real measurements.

CHAPTER 7

EXPERIMENTAL PROCEDURE

7.1 Object of the Experiment

In this experiment, open and closed loop dynamics of the buck converter will be observed. Firstly, in open loop section, component losses that affect converter output voltage will be investigated. Also it will be seen how ESR value of the output capacitor effects the converter output voltage ripple. In DCM (discontinuous conduction mode) the effects of MOSFET and diode paracitic capacitance will be also discussed. In the second part of the experiment, converter closed loop performance will be investigated. For this purpose three performance experiments will be performed. First is the output voltage behaviour during load change, the other is the output voltage behaviour during DC input voltage change and last is the output voltage behaviour during AC input voltage change.

7.2 Theory of Operation

The idealized buck converter circuit is shown below in Figure 79. The power electronic switch opens and closes at a fixed rate of, and its duty cycle is varied to control V_{out} . Capacitor C is assumed to be large enough so that V_{out} has a ripple of less than 5 %. In normal operation, the circuit is in “continuous conduction,” e.g. i_L is always greater than zero.

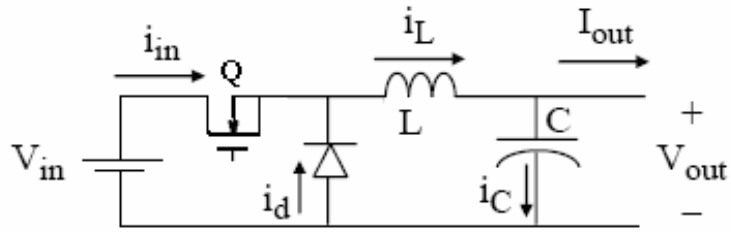


Figure 79 Buck converter.

When the switch is on, the inductor current increases, inducing a positive voltage drop across the inductor and a lower output supply voltage in reference to the input source voltage. When the switch is off, the inductor current discharges, inducing a negative voltage drop across the inductor. Because one port of the inductor is tied to ground, the other port will have a higher voltage level, which is the target output supply voltage. The output capacitance acts as a low-pass filter, reducing output voltage ripple as a result of the fluctuating current through the inductor. The diode provides a current path for the inductor when the switch is off.

A buck converter operates in continuous conduction mode (CCM) if the current through the inductor (I_L) never falls to zero during the commutation cycle. In continuous conduction mode, the output voltage of the converter varies linearly with the duty cycle for a given input voltage;

$$V_o = D \cdot V_i$$

As the duty cycle D is equal to the ratio between t_{on} and the period T , it cannot be more than 1 ($V_o \leq V_i$). This is why this converter is referred to as a step-down converter.

In discontinuous conduction mode, the amount of energy required by the load is small enough to be transferred in a time lower than the whole commutation period. In

this case, the current through the inductor falls to zero during part of the period. In discontinuous conduction mode, the output voltage of the converter does not vary linearly with the duty cycle for a given input voltage;

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

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

The limit between discontinuous and continuous modes is reached when the inductor current falls to zero exactly at the end of the commutation cycle (Figure 80). Inductor current ripple is equal to:

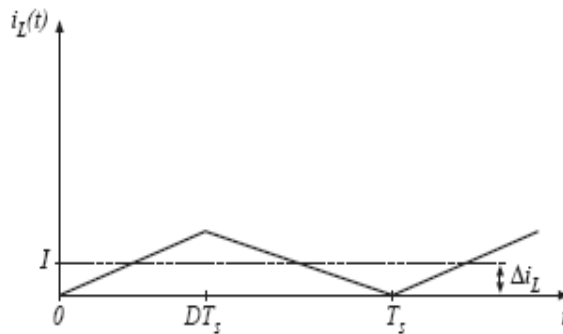


Figure 80 Inductor current of a buck converter in boundary condition.

$$\Delta i_L = \frac{(V_i - V_o)}{2L} DT_s = \frac{V_i DD' T_s}{2L}$$

In continuous conduction mode, the diode current is positive over the entire interval $DT_s < t < T_s$ provided that $I > \Delta i_L$. (I is the dc component of inductor current). Hence, the conditions for operation in the continuous and discontinuous conduction modes are:

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

where I and Δi_L are found assuming that the converter operates in the continuous mode. During the first subinterval, the inductor current supplies the load current and the capacitor is partially charged. During the second subinterval, the capacitor current supplies the load current and the capacitor is partially discharged. The net change in capacitor charge over one switching period is equal to zero and can be found by integrating the $i_c(t)$ waveform:

$$\int i_c = \left(I - \frac{V_o}{R}\right)DT_s + \left(\frac{V_o}{R} - I\right)D'T_s = 0$$

Simplification is applied and I is found as:

$$I = \frac{V_o}{R}$$

By inserting buck converter expressions for I and Δi_L comparison, the following expression is obtained:

$$\frac{DV_s}{R} < \frac{DD'T_s V_i}{2L}$$

Simplification leads to:

$$\frac{2L}{RT_s} < D'$$

This can be also expressed as:

$K < K_{crit}(D)$ for DCM, where

$$K = \frac{2L}{RT_s} \quad \text{and} \quad K_{crit}(D) = D'$$

Discontinuity can be also observed from diode voltage waveform. At discontinuous mode operation, as seen from the results, there is parasitic oscillation on the diode voltage. This is because at the moment the inductor current becomes zero, the diode voltage should adopt the output voltage, and the diode current should remain zero. Nevertheless, for real switches, a network, consisting of parasitic capacitances C_{OS} (which is equal to C_{OSS} , for MOSFETs) of the switch and C_D of the diode, and the inductor L (Figure 81) starts the oscillating at that instant.

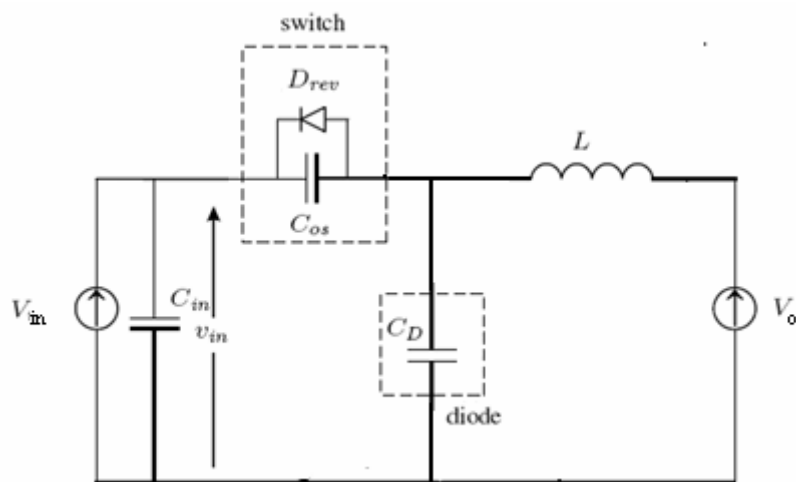


Figure 81 Parasitic network causing oscillations.

The diode voltage oscillation is described approximately as:

$$V_D(t) = V_{in} \cos(\omega_n(t - t_2))$$

where,

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

and t_2 is the time when oscillation starts.

The capacitance C_n , in these expressions is equal to the parallel connection of the switch capacitance and the diode capacitance. The oscillation is ended when the switch is turned on again. For low duty-ratios, this interval may take several oscillation cycles.

The followings are the designed buck converter switch and diode parasitics. These values are taken from the components' datasheets:

- C_{oss} of MOSFET (IRF530) is equal to 450 pF
- C_D of diode (DSS16-01A) is equal 250 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 82). 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.

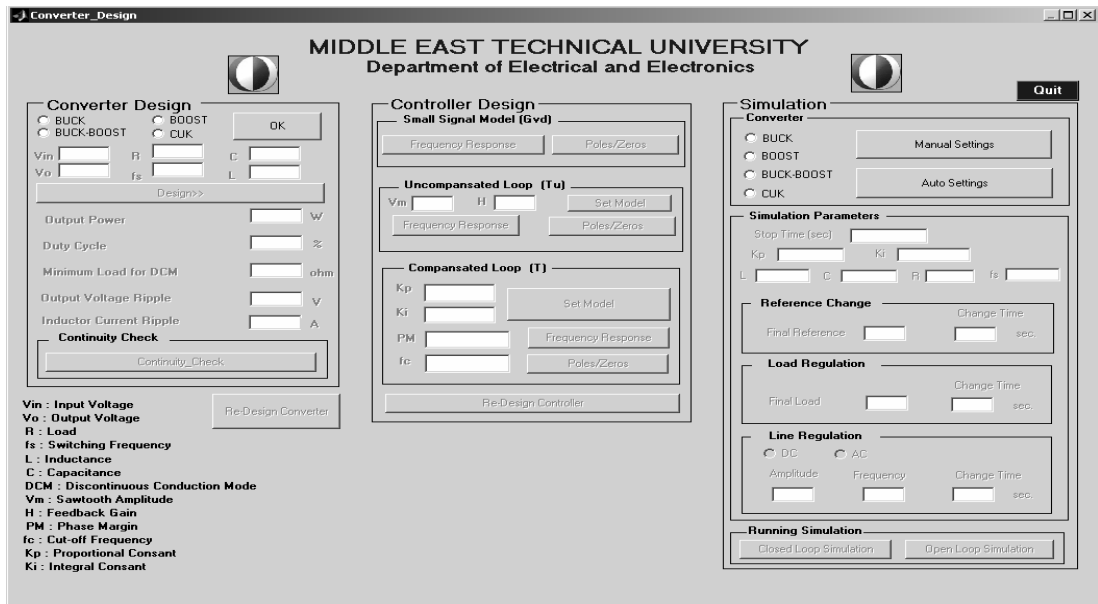


Figure 82 ““Converter Design” GUI.

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 occurring 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: “Frequency Response” and “Poles/Zeros” 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:

- **V_m** : 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 Buck Converter

The general view of the buck converter test box is given in Figure 83. It contains open and closed loop control buttons and probes for external measurements. The functions of each section are shown in Figure 83.

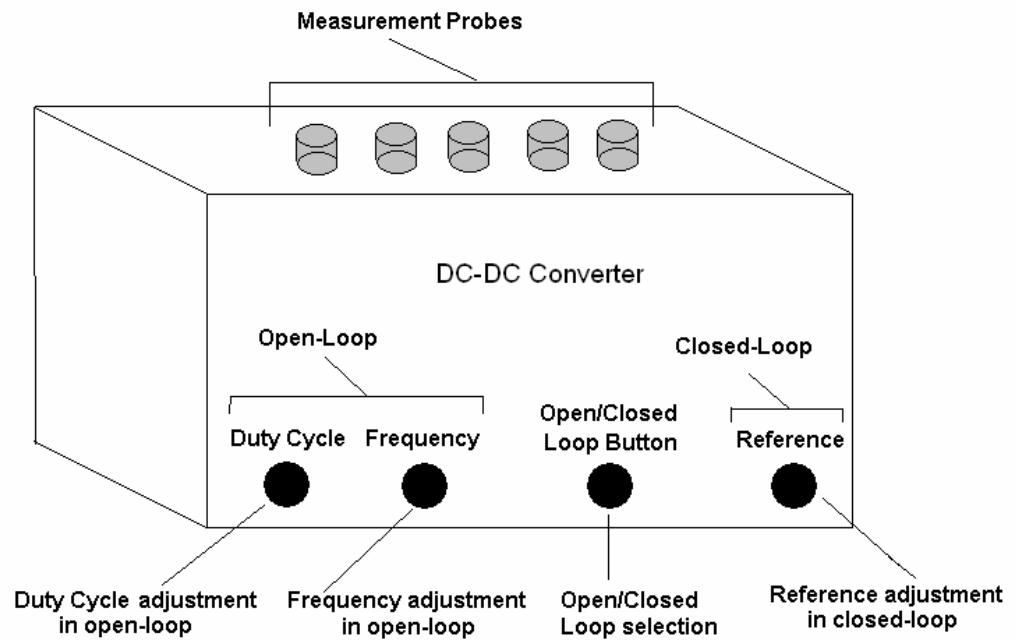


Figure 83 General view of the DC-DC converter test box.

The specification of the buck converter test box is given in Table 7.

Table 7 Buck converter test box specification

Input Voltage	23 V-30 V
Minimum Output Load	5 Ω
Inductor	220 μ H
Capacitor	100 μ F
Operation Frequency	7.7 kHz - 58 kHz
Maximum Duty Cycle	70 %

The general block diagram of the buck converter circuit is shown in Figure 84 and the circuit layout is shown in Figure 85. The circuit consists of three parts: power stage, PWM stage and compensator stage.

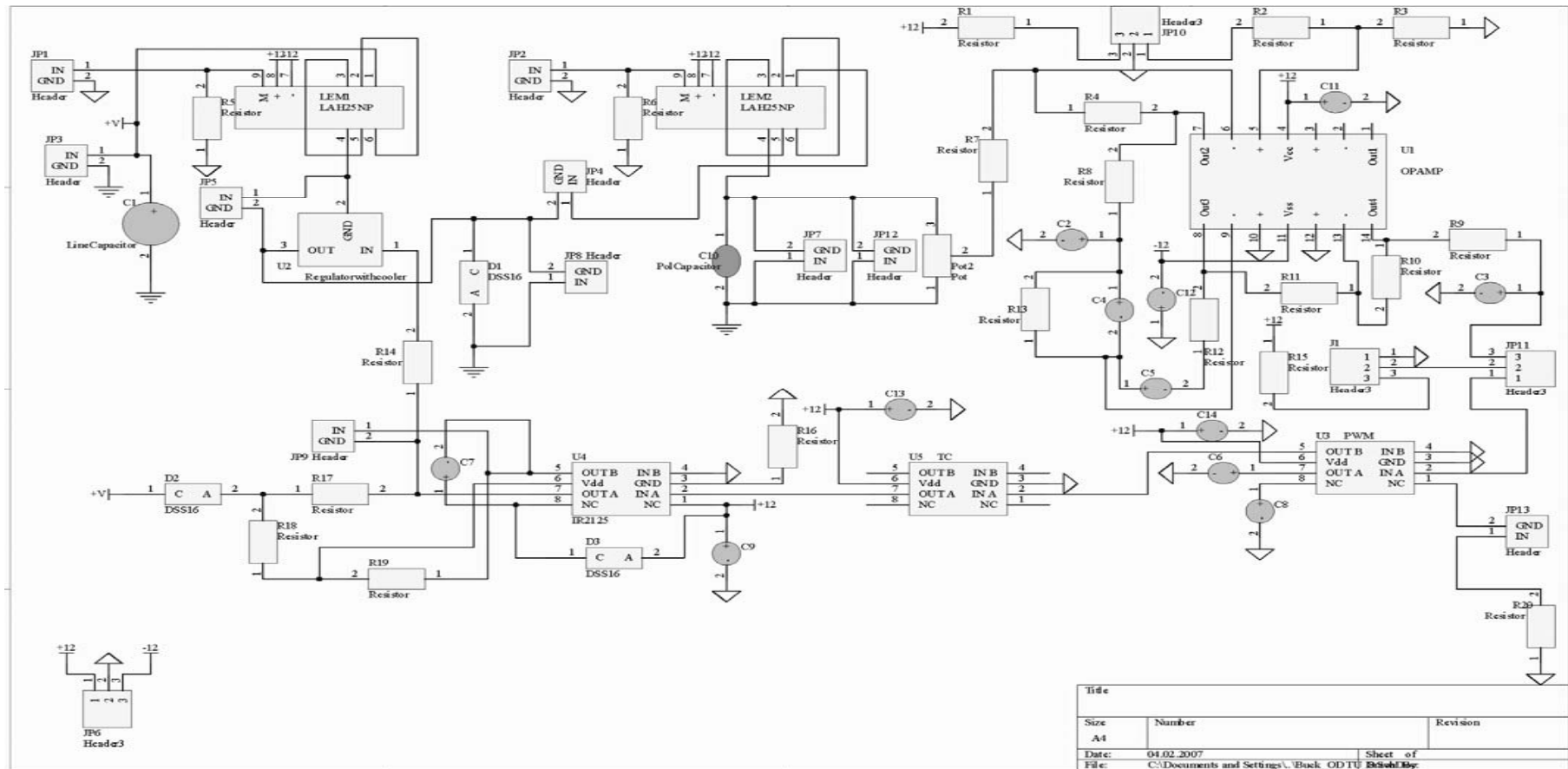


Figure 84 Hardware overview.

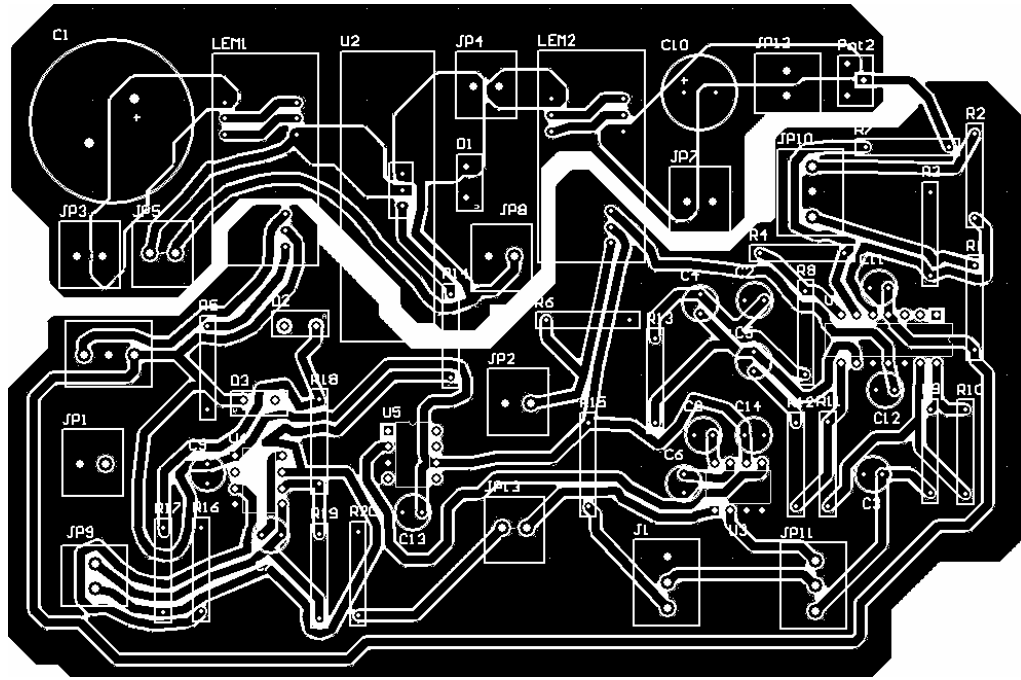


Figure 85 Circuit layout.

The circuit consists of three main stages; power stage, PWM stage and compensator stage. The power stage consists of buck converter and “IR2125” MOSFET gate driver. In the compensator stage, op-amps are used to perform PI compensation. The PWM stage consists of “KA7552” IC and its components, which is used for production of PWM signals to “IR2125” gate driver.

In the compensator stage, “OP1” opamp is a difference amplifier (LM324 is a quad-opamp. These four opamp are identified as OP-1, OP-2, OP3 and OP-4). The reference voltage that is adjusted with “JP-10” potentiometer is extracted from output voltage that is scaled with “Pot-2”. The result is applied to “OP2” opamp input.

“OP2” opamp is used for PI compensator. The transfer function of the PI compensator is given below:

$$G(s) = -\frac{R_{12}}{R_9} \frac{(R_{12}C_6s + 1)}{R_{12}C_6s}$$

where,

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

$$K_i = \frac{1}{R_9 C_6}$$

Because a negative voltage level is obtained at the output of “OP2” opamp, another opamp, “OP3”, is used as an inverting amplifier which has “ $-R_9/R_{10}$ ” conversion ratio.

A PI compensator was generated in accordance with the design needs given in “Design Example” Chapter. To realize this compensator, the following component values are used in circuitry:

- $R_{12} = 330 \Omega$
- $C_6 = 4.7 \mu\text{F}$
- $R_{12} = 673 \Omega$
- $R_{11} = R_{12} = 100 \text{ K } \Omega$

The related proportional and integral gains are:

- $K_p = 2.039$
- $K_i = 618.5$

“S2” switch select the operation of the circuit. If the switch is connected to the “OP3” output the circuit operates in closed loop; if it is connected to the “R₁₂”, the circuit operates in open loop. “J1” potentiometer adjusts the duty cycle of the PWM output in open loop.

“JP9” potentiometer adjusts the frequency of the PWM signal. Notice that switching frequency can be adjusted both in the open loop and closed loop operations.

As gate driver, “IR2125 High and Low Side MOSFET Driver” IC is used. This driver has undervoltage lockout and cycle-by-cycle over current protection features. The components used in the buck converter are listed in Table 8.

Table 8 Buck converter part list

Component	Reference	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	$V_{DSS} = 100 V$, $R_{DS(ON)} = 0.64 \Omega$, $I_D = 14 A$, $C_{oss} = 220pF$	International Rectifier, IRF530
Inductor	JP2	1	220 μH , 5 A	Coilcraft, PCV-2-224-05,
Capacitors	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	

Table 8 (continued)

ICs	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 k Ω , 1/4 W	
	R2	1	10 Ω , 1/4 W	
	R5	1	20 k Ω , 1/4 W	
	R6	1	332 Ω , 1/4 W	
	R8	1	22 k Ω , 1/4 W	
	R18, R14	1	22 k Ω , 1/4 W	
	R13	1	620 k Ω , 1/4 W	
	R19	1	160 Ω , 1/4 W	
	R15	1	8.2 k Ω , 1/4 W	
	R11	1	1 k Ω , 1/4 W	
	R12	1	8.2 k Ω , 1/4 W	
	R9	1	1.1 k Ω , 1/4 W	
Potentiometers	JP9	1	10 k Ω	
	JP10	1	10 k Ω	
	J1	1	1 k Ω	

7.4 Apparatus

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

Table 9 Apparatus used in experiment

Component	Quantity	Specification
Buck Converter	1	Given below
Oscilloscope	1	Agilent 54624A 100 MHz
DC Power Supply	2	30 V 6 A
Rheostat	2	420 Ω 11 A
PC (“Converter_Design” Tool installed)	1	Standart

7.5 Experimental Procedure

7.5.1 Open Loop Characteristics

This experiment is intended to show the open loop behaviors of the buck converter 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)

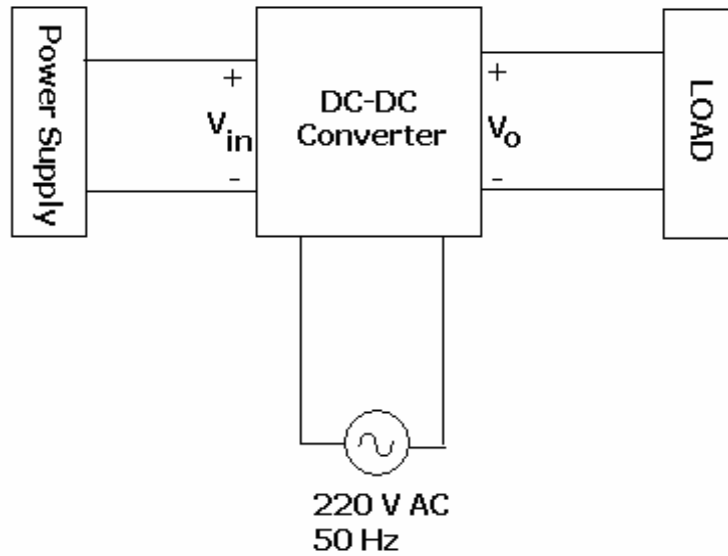


Figure 86 Converter hardware set-up (open-loop).

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 13 Ω . Turn on the power supply.

By using FREQUENCY button, adjust the switching frequency to 20000 Hz. By using DUTY CYCLE button, adjust the duty-cycle to 50 %. Connect the oscilloscope probe to the related measurement probes of the buck converter test box and observe waveforms of the MOSFET voltage, diode voltage, inductor current, output voltage and output voltage ripple. In the “Converter Design“ GUI, enter the design parameters and observe the simulation results. Measurement results are illustrated below.

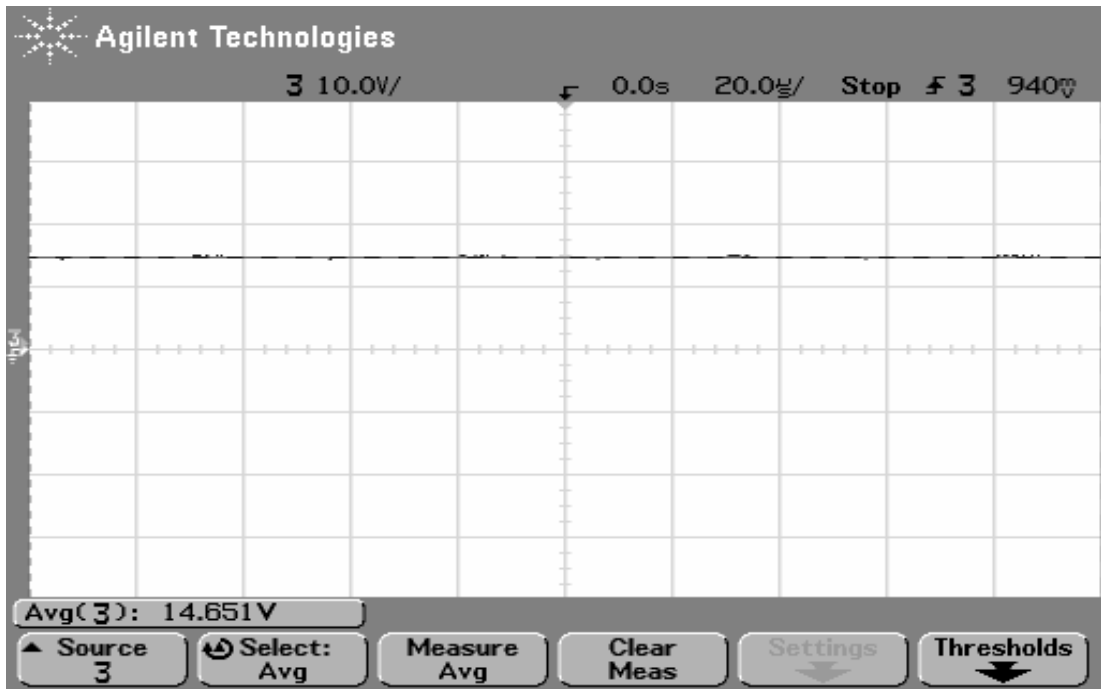


Figure 87 Measurement result-Buck converter output voltage (oscilloscope channel is at DC mode).

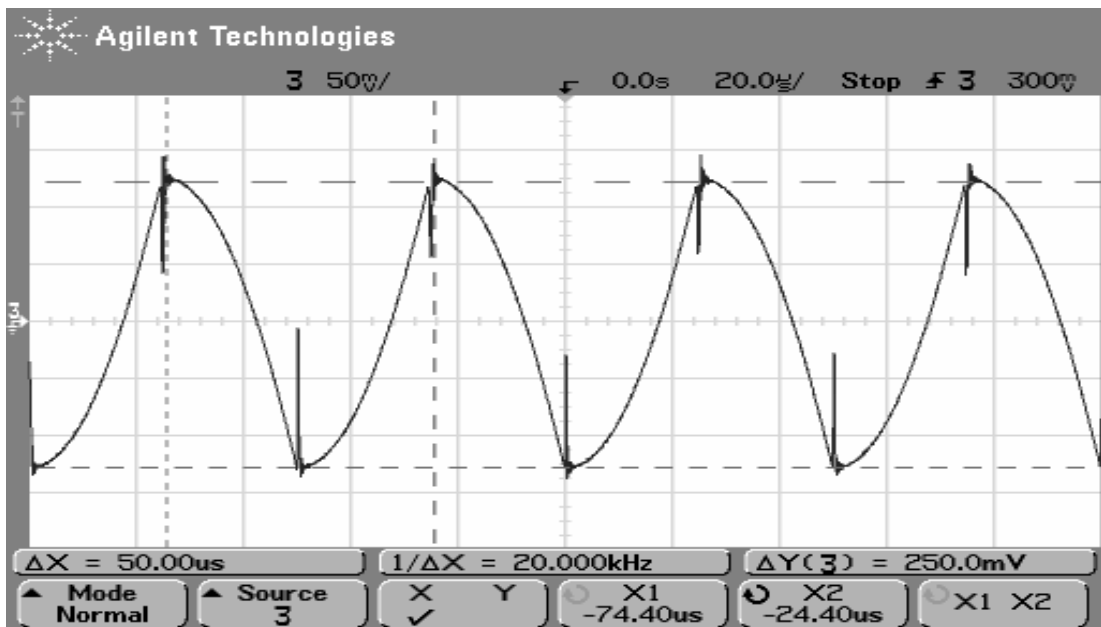


Figure 88 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).

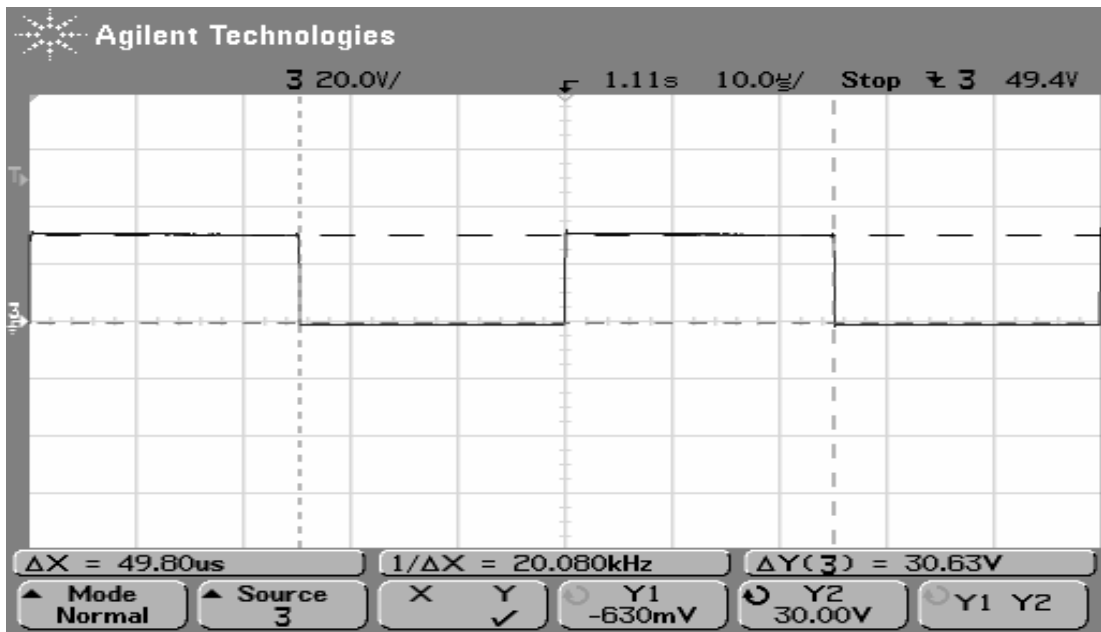


Figure 89 Measurement result-Buck converter diode voltage.

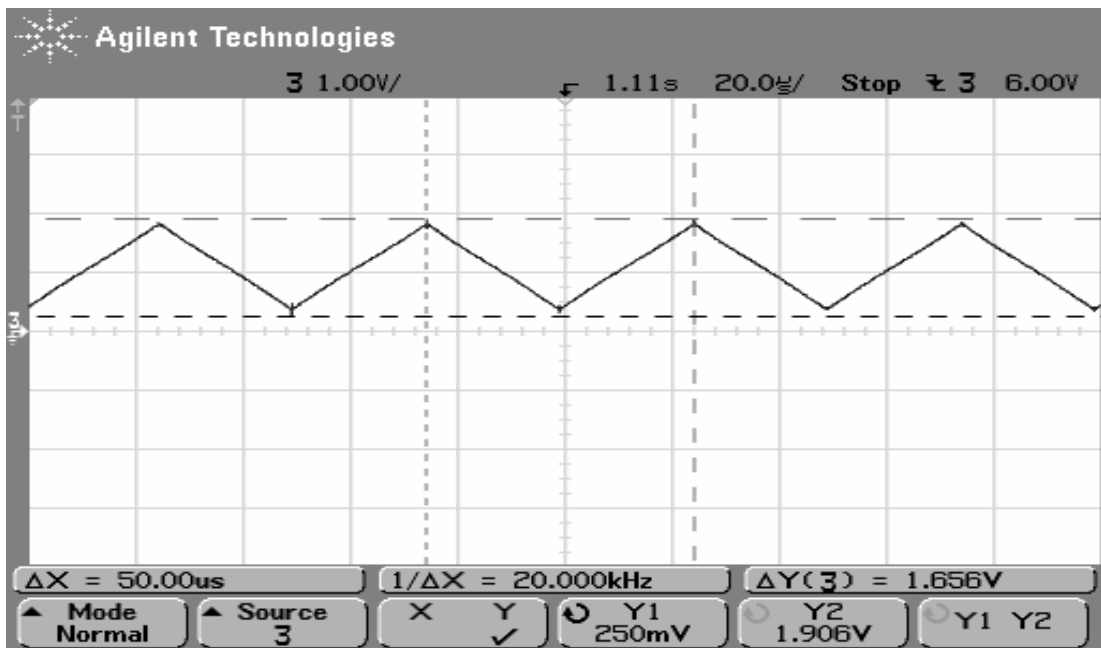


Figure 90 Measurement result-Buck converter inductor current.

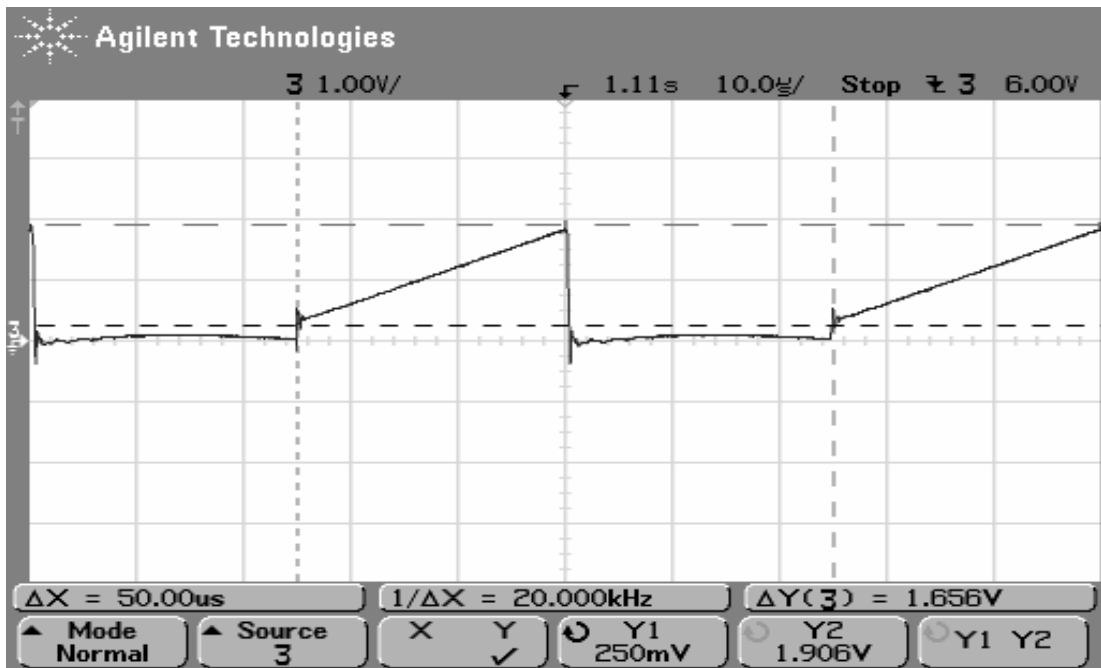


Figure 91 Measurement result-Buck converter input current.

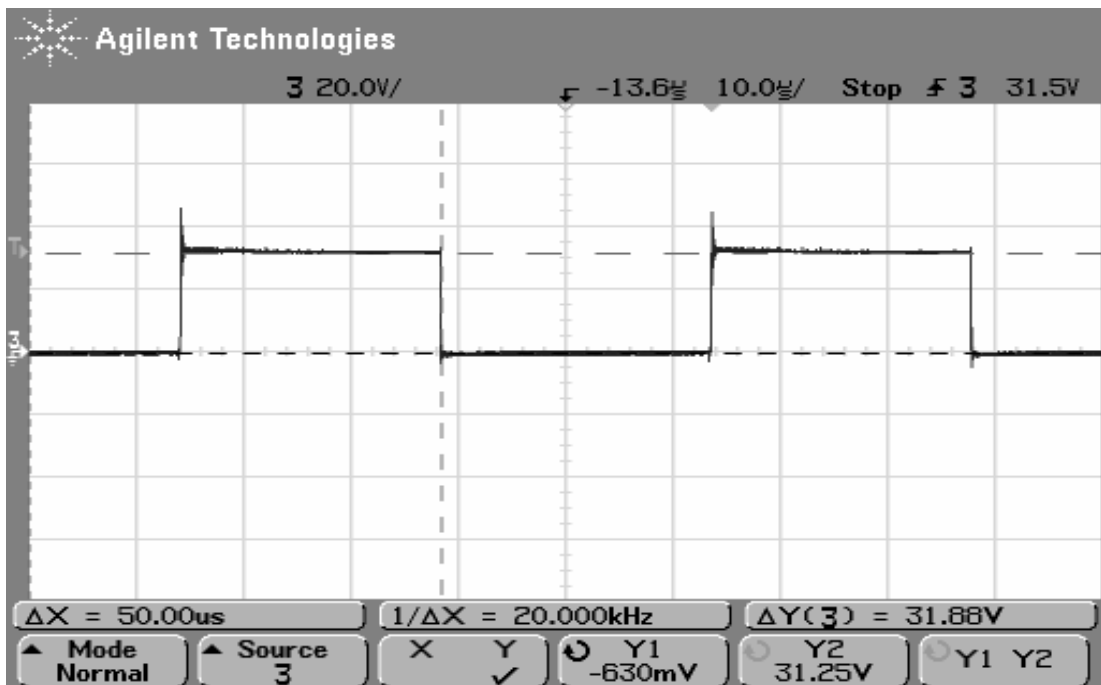


Figure 92 Measurement result-Buck converter switch voltage.

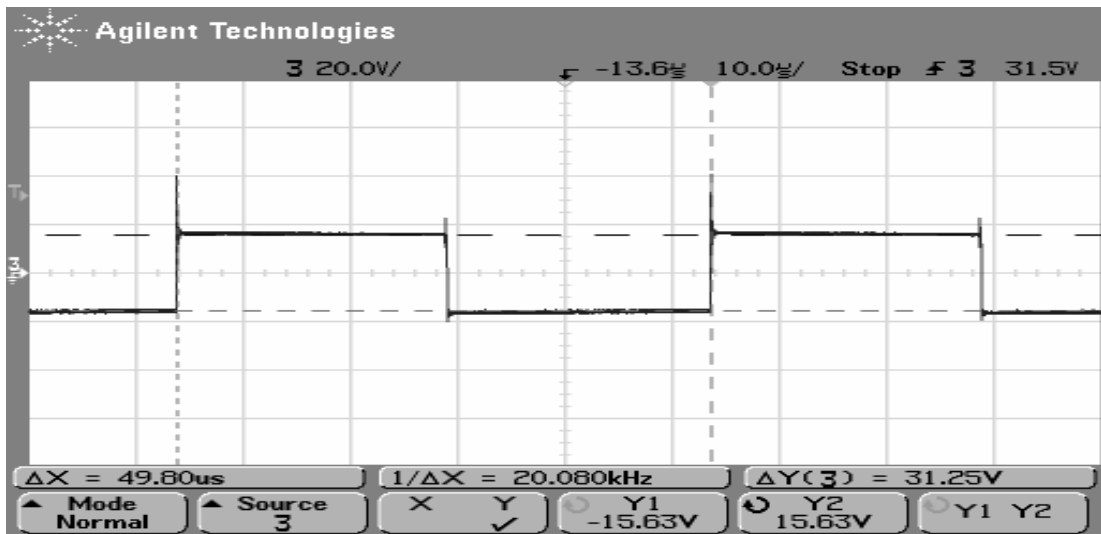


Figure 93 Measurement result-Buck converter inductor voltage.

- 3- Repeat step 2 for 10, 20, 30, 50, 60, 70 % duty cycle.
- 4- Set the duty cycle to the 50%, load to 25 Ω 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.

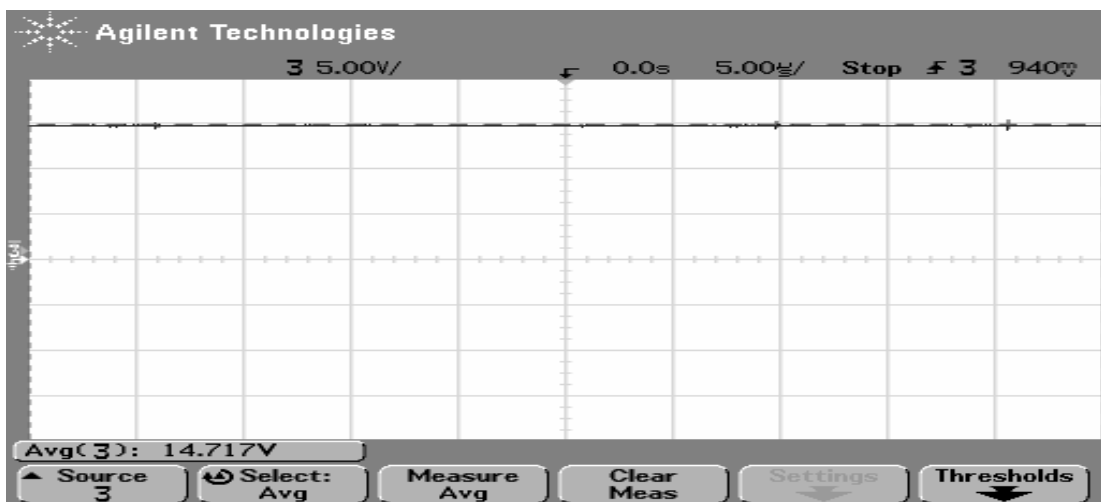


Figure 94 Measurement result-Buck converter output voltage (oscilloscope channel is at DC mode).

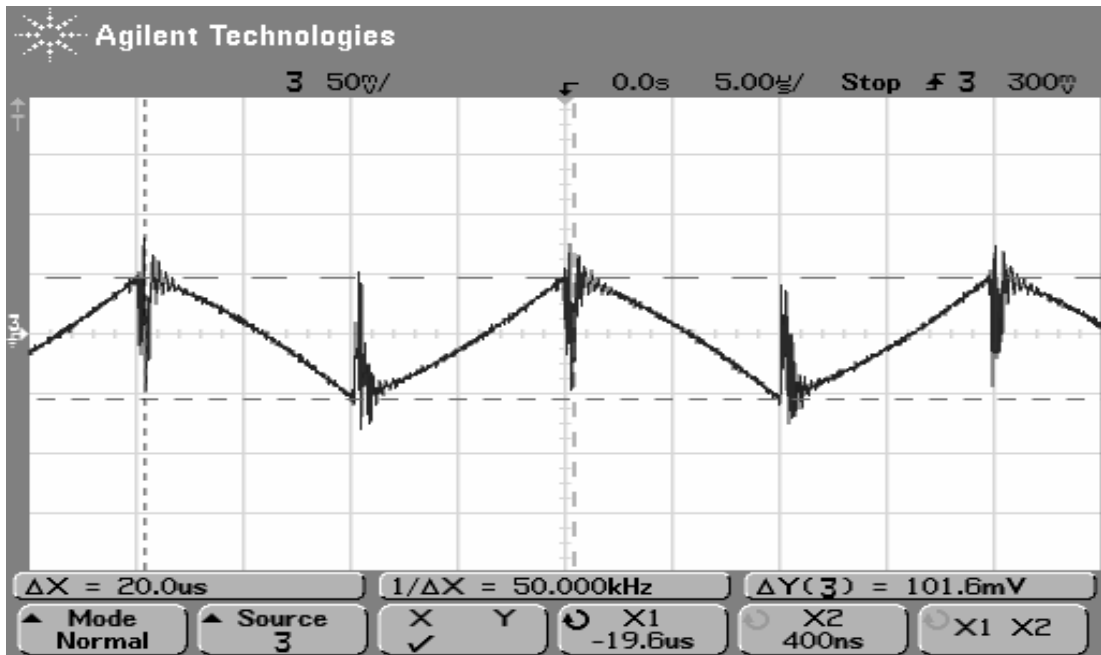


Figure 95 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).

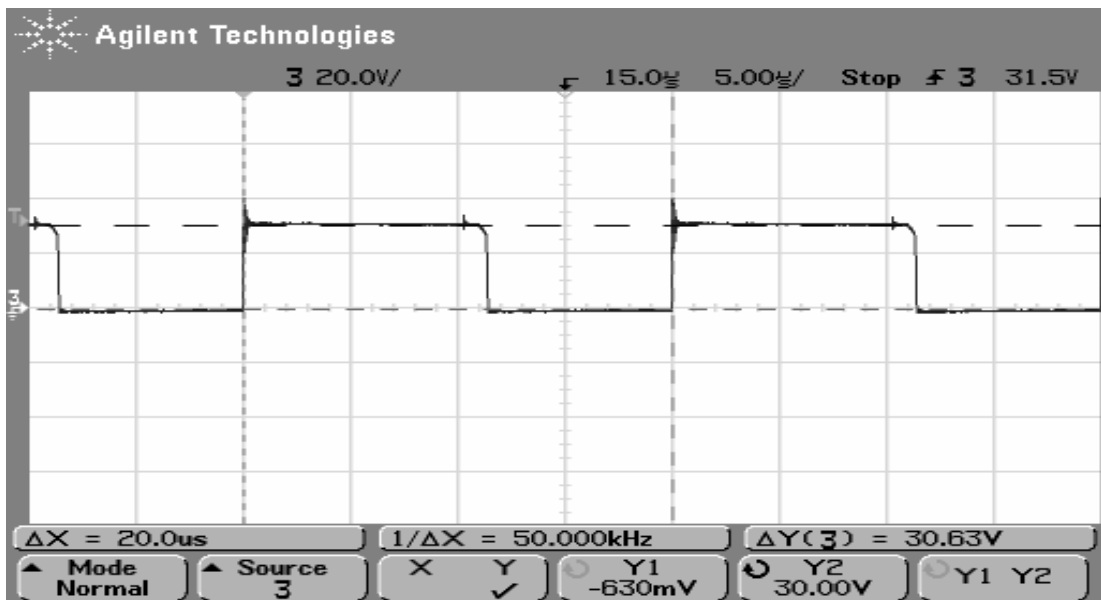


Figure 96 Measurement result-Buck converter diode voltage.

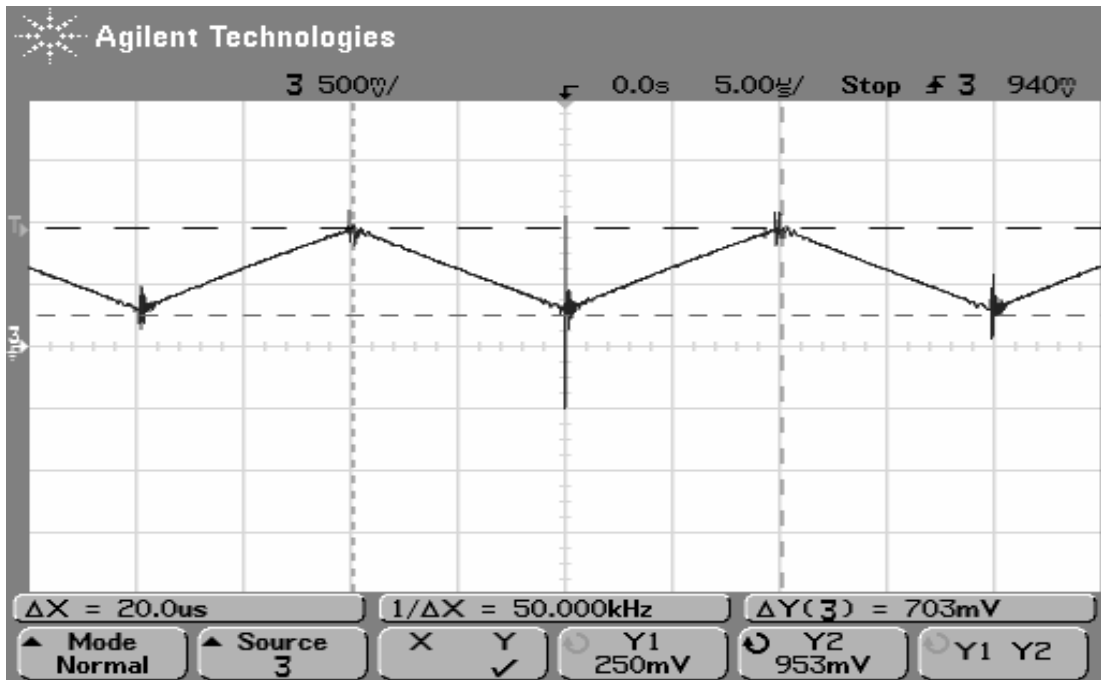


Figure 97 Measurement result-Buck converter inductor current.

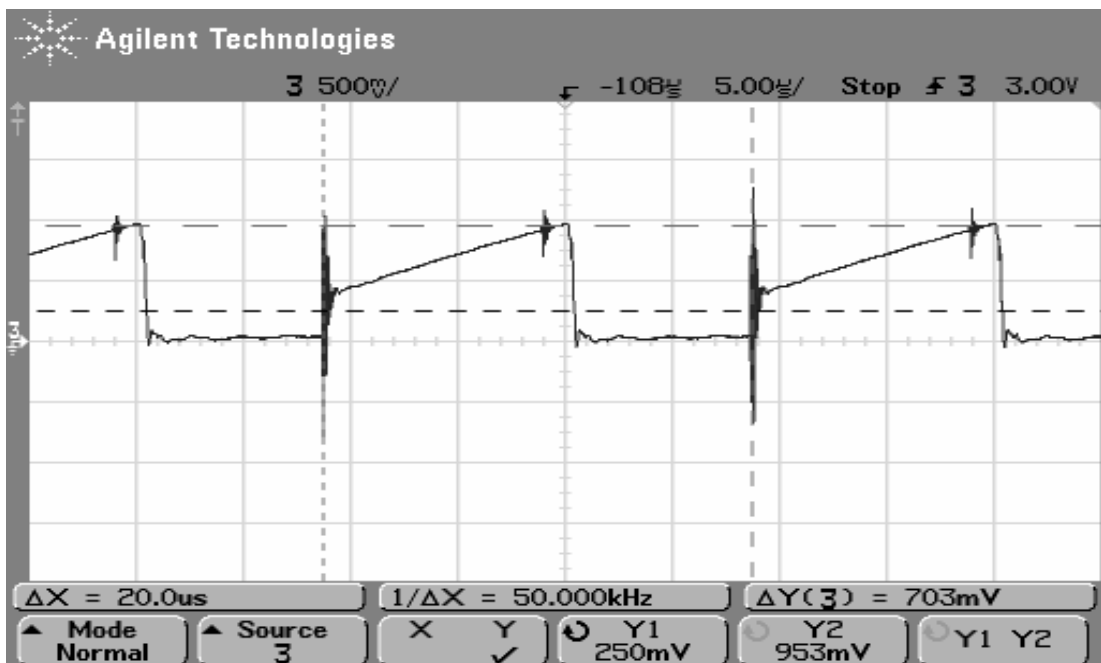


Figure 98 Measurement result-Buck converter input current.

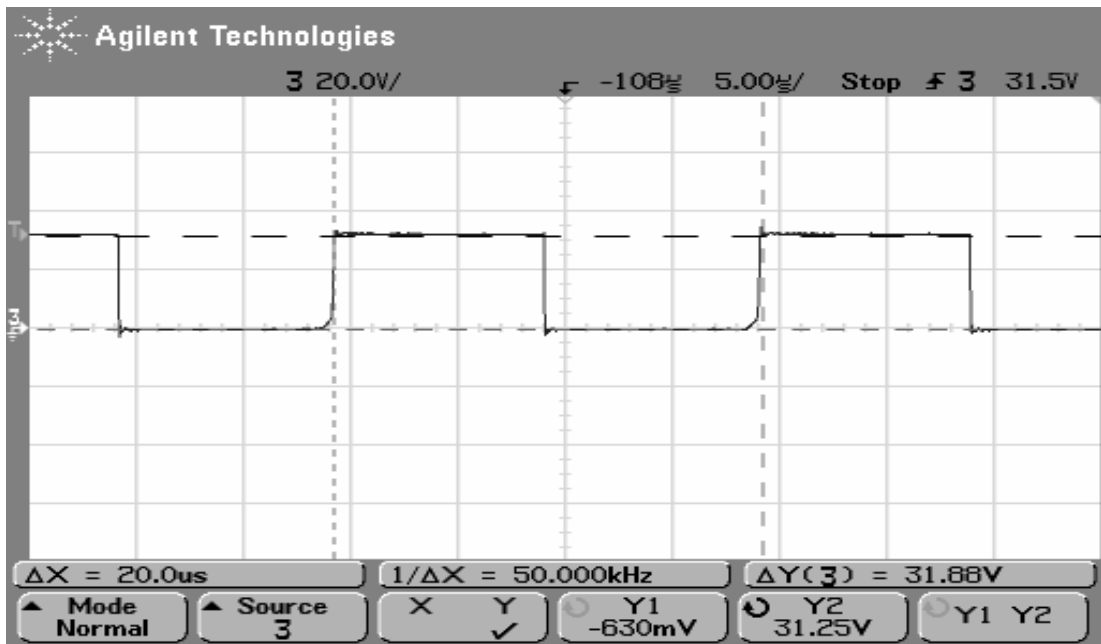


Figure 99 Measurement result-Buck converter switch voltage.

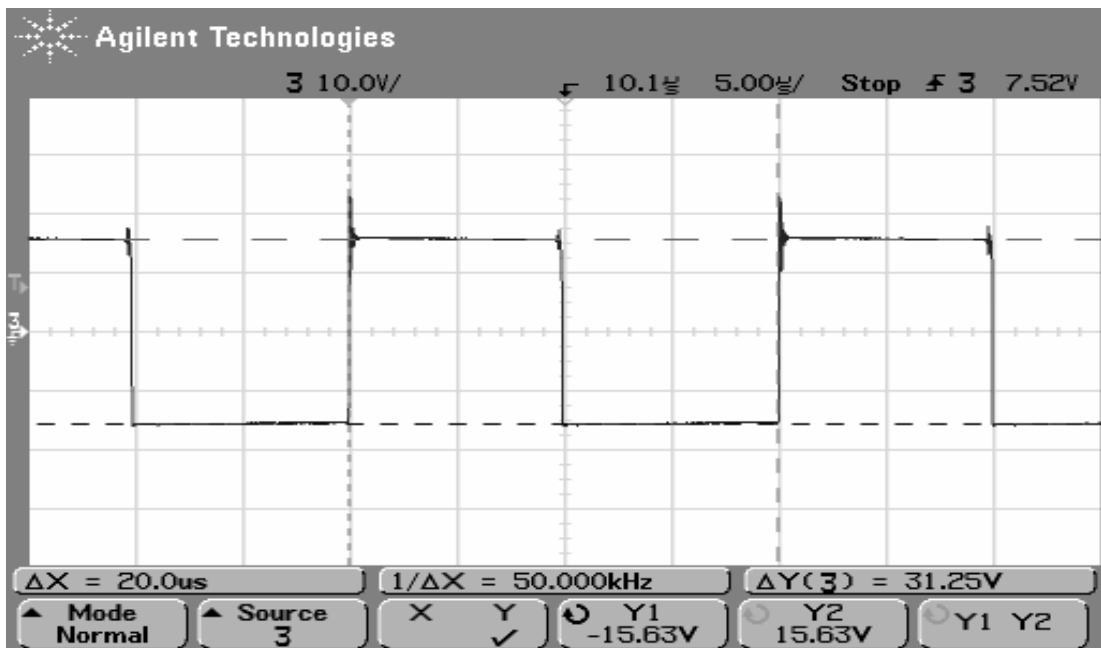


Figure 100 Measurement result-Buck converter inductor voltage.

- 5- Repeat step 4 for switching frequency 10, 30 and 40 kHz.
- 6- Turn off the power supply, disconnect the rheostat from the buck converter test box and by using multimeter adjust the rheostat to the 25 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.

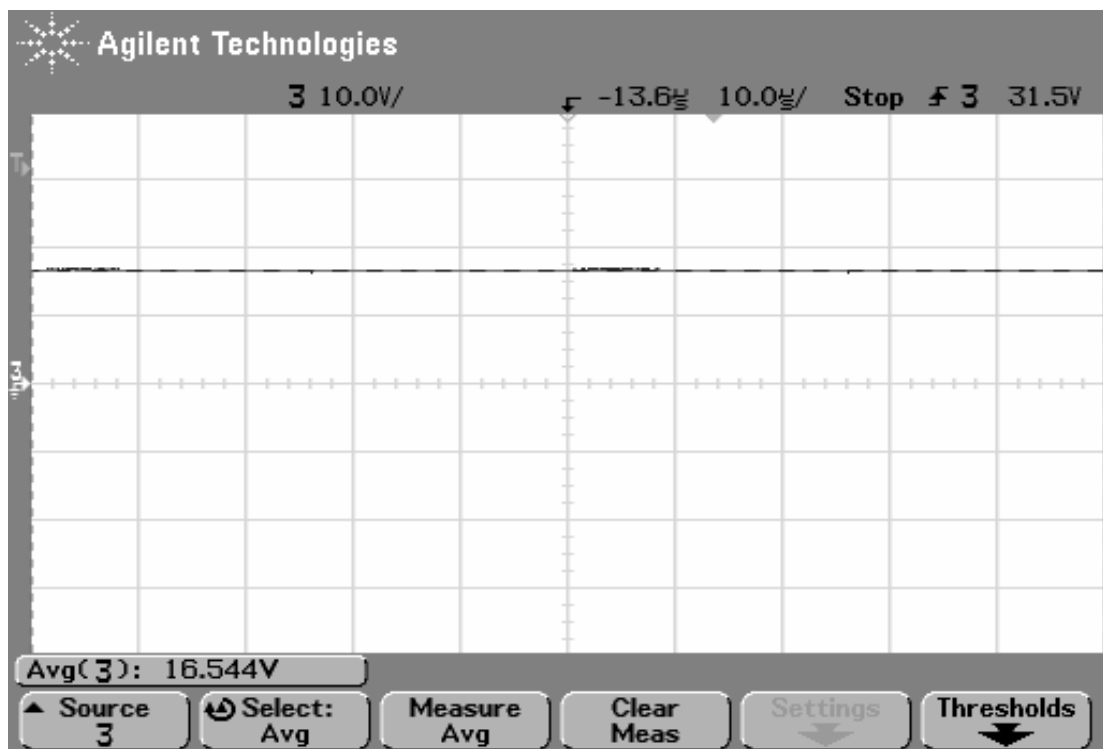


Figure 101 Measurement result-Buck converter output voltage

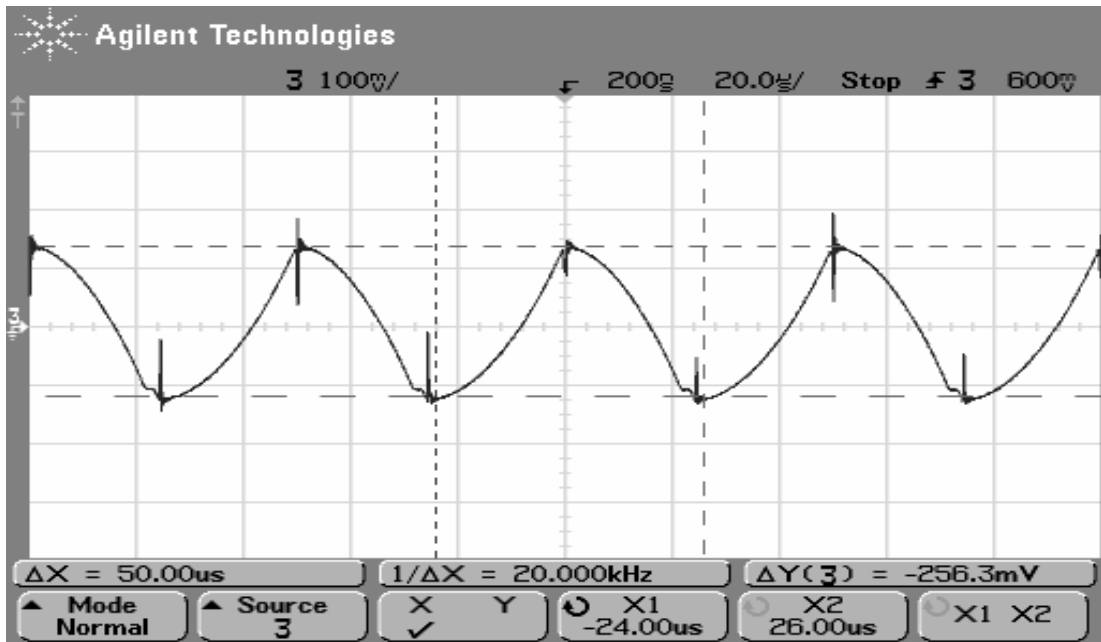


Figure 102 Measurement result-Buck converter output voltage (oscilloscope channel is at AC mode).

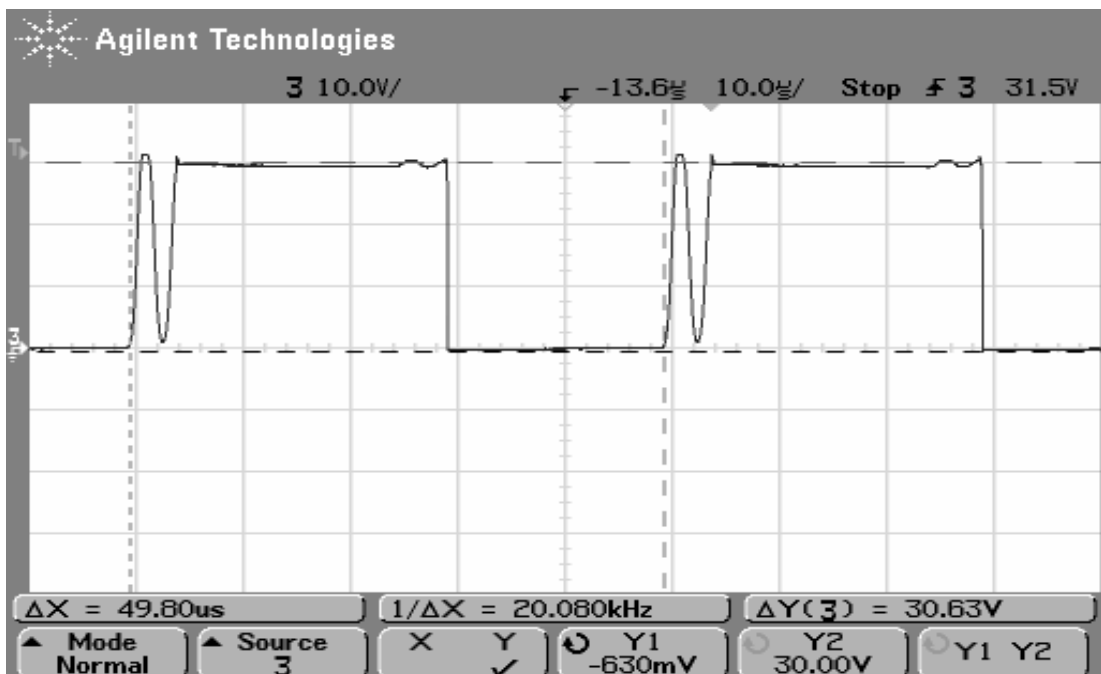


Figure 103 Measurement result-Buck converter diode voltage.

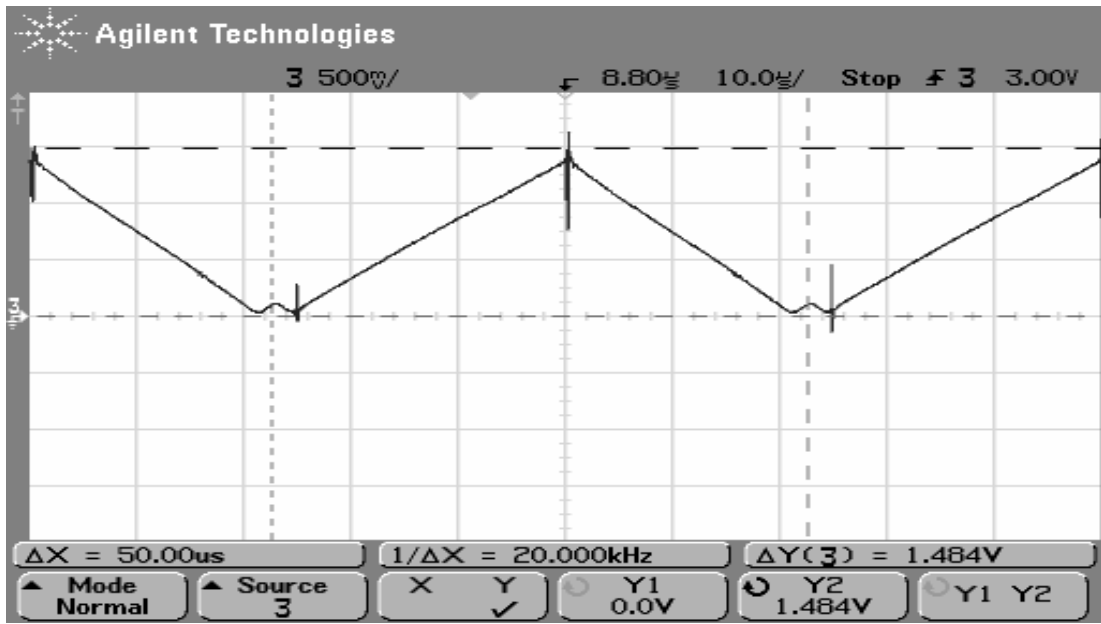


Figure 104 Measurement result-Buck converter inductor current.

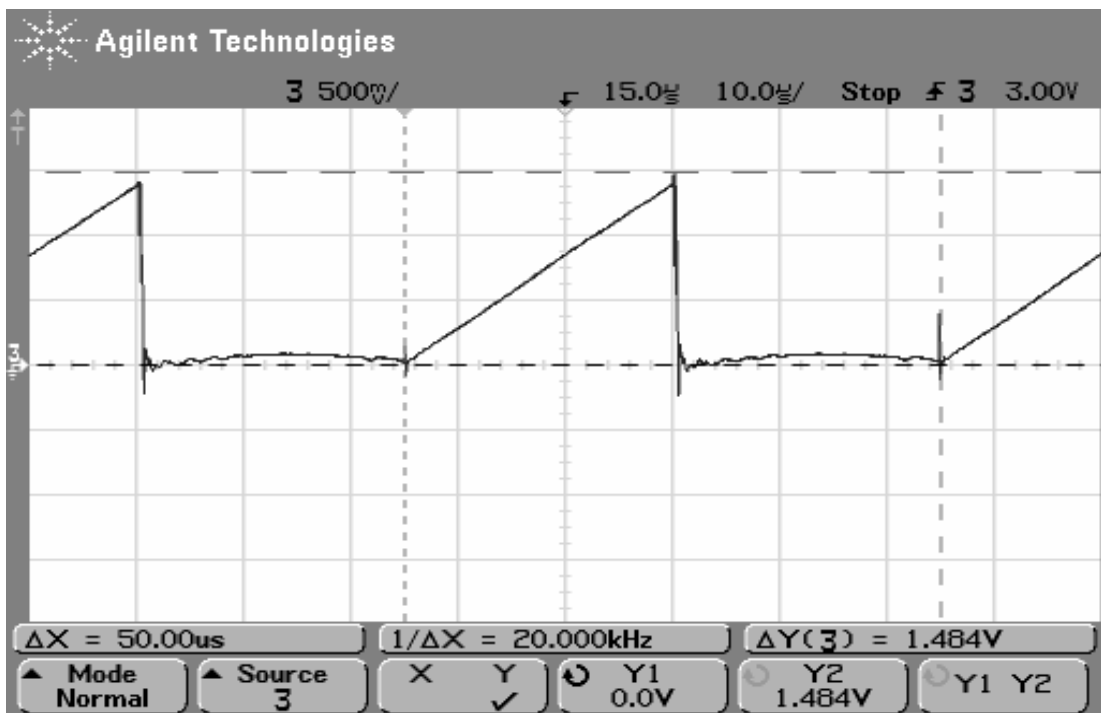


Figure 105 Measurement result-Buck converter input current.

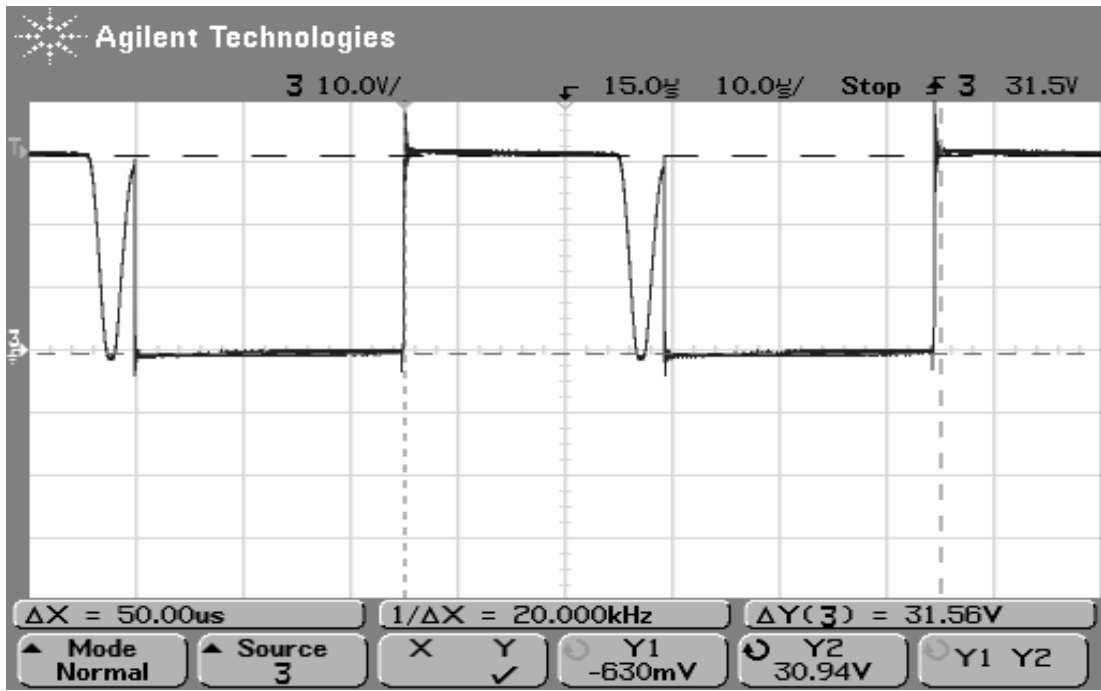


Figure 106 Measurement result-Buck converter switch voltage.

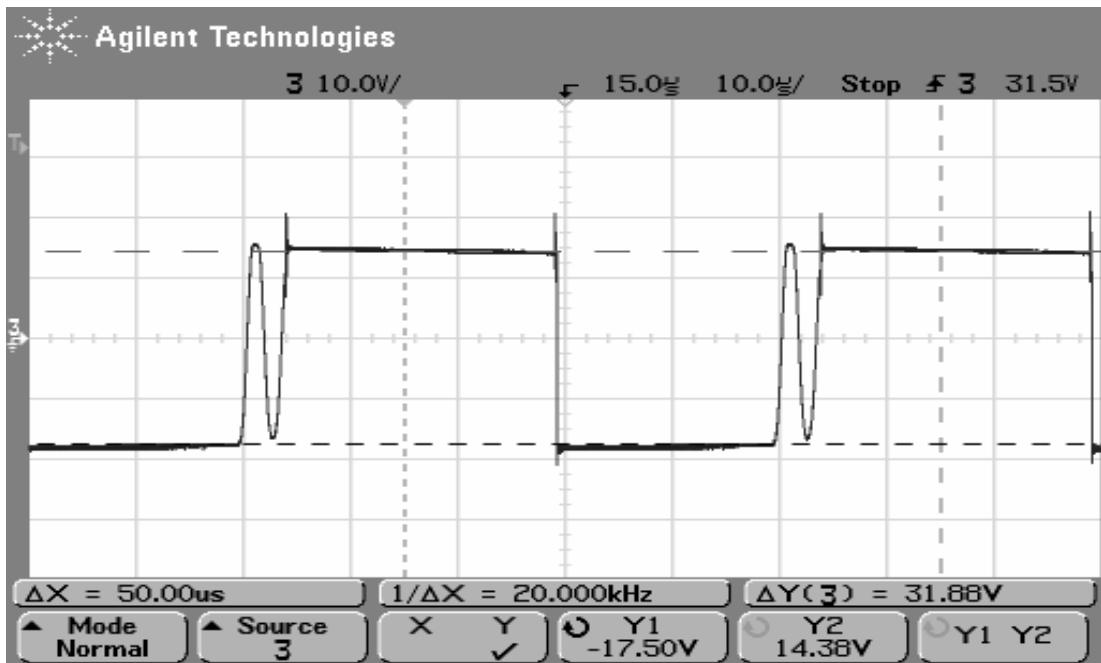


Figure 107 Measurement result-Buck converter inductor voltage.

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 voltages operating in discontinuous conduction mode.

7.5.2 Closed Loop Characteristics

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

7.5.2.1 Procedure

- 1- In the “Converter Design” tool set the following parameters (Table 10).

Table 10 Closed Loop Simulation Parameters

Reference Change	Final Reference: 0 V	Change Time: 0.06 s
Load Regulation	Final Load: 25 Ω	Change Time: 0.03 s
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.06 s
Line Regulation (AC)	Amplitude: 2 V peak ; Frequency: 50 Hz	Change Time: 0.06 s

Then press the “closed-loop simulation” button. After simulation is terminated, observe the dynamic behaviour of the buck converter during load change.

2- Power off the power supply, adjust the rheostats to $7\ \Omega$ and set-up the following hardware configuration (Figure 108).

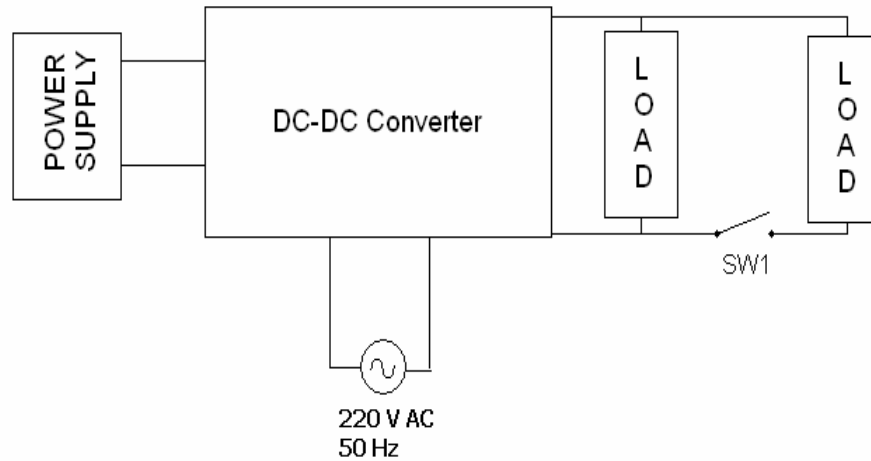


Figure 108 Converter hardware set-up (closed-loop) for load regulation.

Turn the “Open/Closed Loop” switch to closed loop position and turn on the power supply. Adjust the output voltage by changing the “Reference” potentiometer. Before starting the experiment, switch “SW-1” must be closed and oscilloscope must be connected to the converter output. At any time, open the switch “SW-1” so that the load is suddenly changed from $7\ \Omega$ to $25\ \Omega$. Record the the output voltage change. Measurement result is illustrated below (Figure 109).

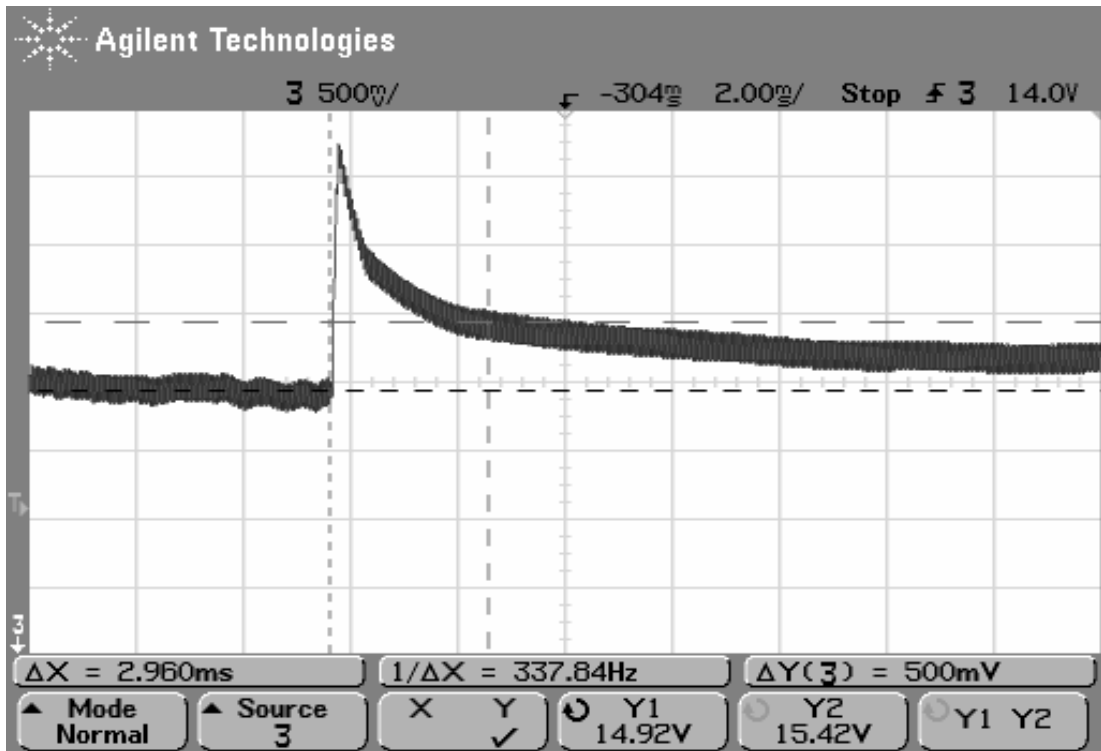


Figure 109 Output voltage characteristic during load change.

3- In the “Converter Design” tool set the following parameters (Table 11).

Table 11 Closed Loop Simulation Parameters

Reference Change	Final Reference: 0V	Change Time: 0.06 s
Load Regulation	Final Load: 25 Ω	Change Time: 0.06 s
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.03 s
Line Regulation (AC)	Amplitude: 2.3 V peak; Frequency: 50 Hz	Change Time: 0.06 s

Then press the “Closed-Loop Simulation” button. After simulation is terminated, observe the dynamic behaviour of the buck converter output voltage during DC input voltage change.

4- Turn off the power supply, disconnect the second rheostat from the circuit and adjust the first one to 7Ω . Then set-up the following hardware configuration.

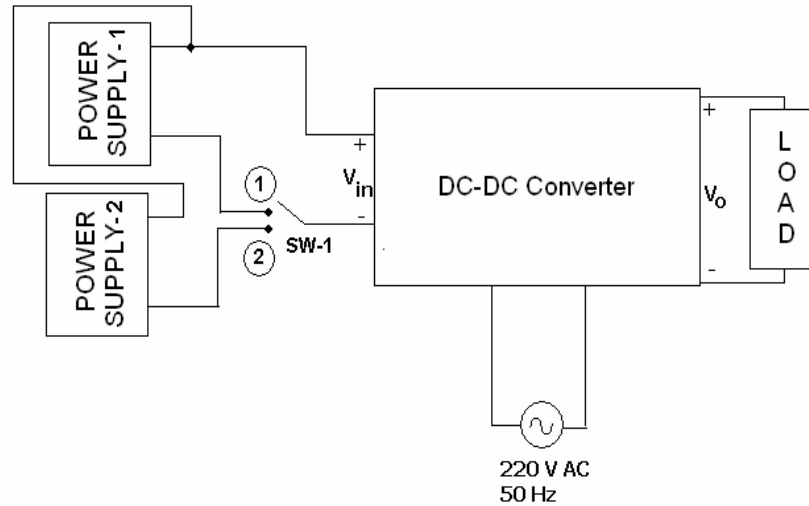


Figure 110 Converter hardware set-up (closed-loop) for DC line regulation.

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 the output voltage during DC line change. Measurement result is illustrated below (Figure 111).

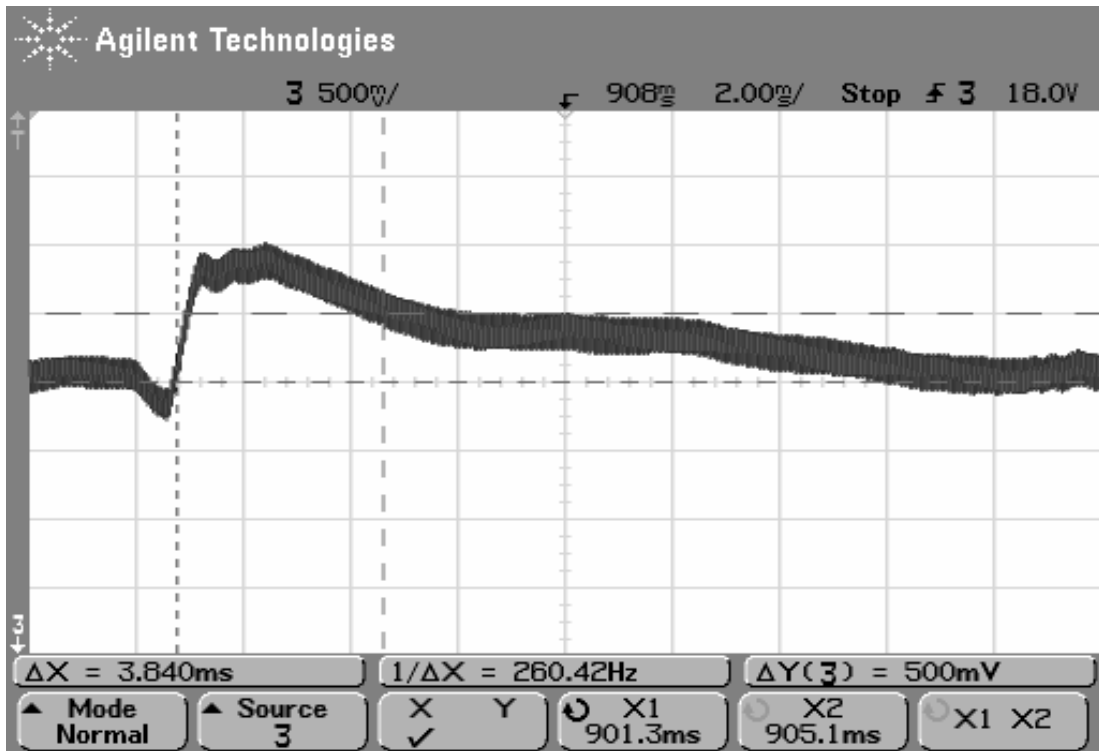


Figure 111 Measurement result-Buck converter load characteristics at DC line change (at $t = 0.03$ s, 5 V DC is added to the DC line input 30 V).

5- In the “Converter Design” tool set the following parameters (Table 12).

Table 12 Closed Loop Simulation Parameters

Reference Change	Final Reference: 0 V	Change Time: 0.06 s
Load Regulation	Final Load: 25 Ω	Change Time: 0.06 s
Line Regulation (DC)	Amplitude: 5 V	Change Time: 0.06 s
Line Regulation (AC)	Amplitude: 4.6 V peak; Frequency: 50 Hz	Change Time: 0.03 s

Then press the “Closed-Loop Simulation” button. After simulation is terminated, observe the dynamic behaviour of the buck converter during AC input voltage change.

6- 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, obtain 4.6 V AC voltage on variac secondary side. Turn off the variac and then set-up the following hardware configuration.

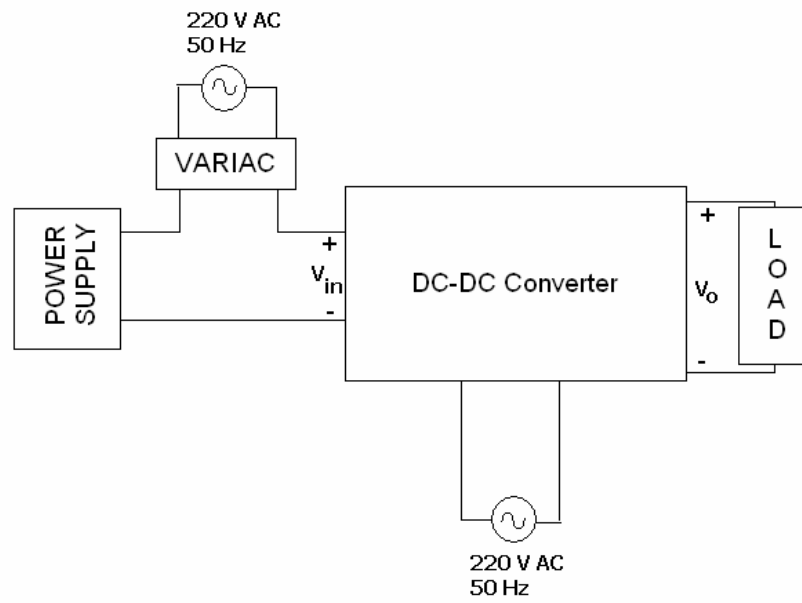


Figure 112 Converter hardware set-up (closed-loop) for AC line regulation

Turn on the variac and then power supply. The oscilloscope must read the output voltage. In this configuration the input voltage of the converter 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. Measurement result is illustrated below (Figure 113).

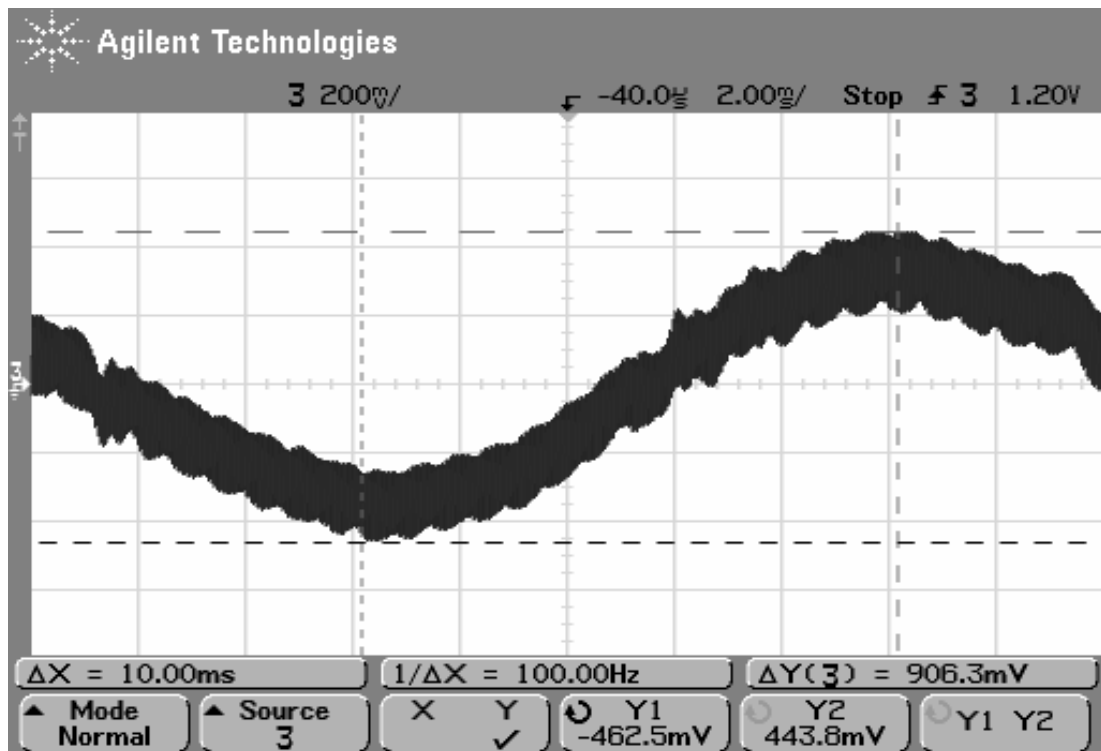


Figure 113 Measurement result-Buck converter output voltage at 4.6 V peak-to-peak AC line change (oscilloscope at AC Mode).

7.5.5.2 Study Questions

- 1- Discuss the difference between open and closed loop control.
- 2- Perform closed-loop simulation for five different K_p and K_i controller parameters and observe the converter output voltage during the same line and load changes as given previously. Explain the effect of the controller on the output voltage.
- 3- Is PI controller is sufficient for buck converter closed-loop control? Propose another more efficient controller and explain the reasons.

CHAPTER 8

CONCLUSION

In this thesis a buck converter is developed. First, a steady-state analysis of buck converter has been performed. It is known that this analysis is only used for stable, steady-state operating condition. But this is not sufficient because, in reality, there are also transient conditions in a converter operation that cannot be modeled only using steady-state analysis. For dynamic modeling of the buck converter, small-signal analysis is used in this thesis. This approximation is very practical in complete converter modeling and control. In this thesis, proportional-plus-integral (PI) controller is used as control approach that also needs derived small-signal model of a buck converter.

Developed models have been simulated using MATLAB-Simulink and accordingly a buck converter was manufactured. It have been seen that the measurement results are very close to the simulation results. Some of these values are time response of the designed converter to changes in reference signal, the converter output voltage response during load and line voltage change, inductors and switch currents.

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.

PI parameters tuning methodology used in the GUI is based on frequency response analysis of the buck converter with a compensator to obtain an operating point that is stable and resistive to switching ripple and distortions. The simulation and measurement results show that the designed and applied compensator have been satisfy the design needs.

PWM IC used in the thesis has a duty-cycle limitation. Maximum 70 % duty-cycle may be applied to the converter power MOSFET. This means that the converter output power has also a limitation. On the other hand, at 0 % - 70 % duty cycle range , this PWM IC performance satisfies all the needs. Another IC – which has a maximum duty-cyle limit greater than 70 % - may exchange the converter output power range. The manufactured converter can operate upto 100 % duty-cycle if the given converter specificaitons are considered during operation.

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 news 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. More powerful IC selection (for example PWM IC) may improve the output power of the converter.

REFERENCES

[1] wikipedia.org, DC-DC Converter, Aug 2006,

http://en.wikipedia.org/wiki/DC_to_DC_converter

[2] altera.com, Power Supply Regulation, Aug 2006,

<http://www.altera.com/support/devices/power/regulators/pow-regulators.html>

[3] wikipedia.org, Voltage Regulator, Aug 2006,

http://en.wikipedia.org/wiki/Voltage_regulator

[4] answers.com, Voltage Regulator, Aug 2006,

<http://www.answers.com/topic/voltage-regulator>

[5] G. Ledwich , DC DC Converter Basics, 1998,

<http://www.ece.msstate.edu/courses/design/2006/spring/design1/mvops/deliverables/Presentations/Midterm%20Design%20PDR.ppt>

[6] Y H Chin, MOTOROLA, AN1547/D,

http://www.eetkorea.com/ARTICLES/2004MAY/2004MAY18_ICD_POW_AN02.PDF#search=%22It%20is%20basically%20a%20forward%E2%80%93mode%20regulator%20and%20is%20also%20the%20basic%20building%20block%20of%20all%20the%20forward%E2%80%93mode%20topologies.%20%22

- [7] powerelectronics.com, Buck-Converter Design Demystified, 2004,
http://powerelectronics.com/power_systems/dc_dc_converters/power_buckconverter_design_demystified/
- [8] wikipedia.org , Buck Converter, Aug 2006,
http://en.wikipedia.org/wiki/Buck_converter
- [9] R. W. Erickson and D. Maksimovic, University of Colorado, Fundamental of Power Electronics-Second Edition
- [10] The MathWorks, MATLAB Tool, Documentation>Graphical User Interfaces, 1994-2006
http://www.mathworks.com/access/helpdesk/help/techdoc/creating_guis/creating_guis.html
- [11] Control Tutorials for MATLAB, The University of Michigan, Aug 1996,
<http://www.engin.umich.edu/group/ctm/freq/freq.html>
- [12] Wikipedia, Phase Margin, Sept 2006,
http://en.wikipedia.org/wiki/Phase_margin
- [13] 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.