Master Thesis
Electrical Engineering

Load Identification of DC-DC Buck Converter

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Abstract

The thesis is to develop Signal Processing methods which increase the performance, functionality and reliability of dc-dc converters which is part of an ongoing project of Ericsson together with Blekinge Institute of Technology.

The aim of this project is to model the buck converter system of Ericson's BMR450 using MATLAB Simulink and develop methods to identify the capacitive load. Our first approach is to derive the equation which gives relation of capacitive load with output voltage in time domain analysis. Our second method deals with resonant point of frequency response of buck converter using Linearization method. Our final method deals in frequency domain analysis using FFT.

For different values, we calculated the capacitive load values using proposed methods and compared them to the original values to observe the percentage of errors.

Acknowledgement

We would like to thank our supervisor Anders Hultgren for his guidance, support, and valuable comments during the period of this project. We are grateful to Anders Hultgren for all the time he spent on giving suggestions and technical support for the project.

Furthermore, we would like to thank staff at Electrical Engineering department, Blekinge Institute of Technology who helped us in all aspects.

Finally, we would like to thank our Parents and Friends for their unconditional support and love though our life.

Table of Contents

List of Figures

Introduction

1. INTRODUCTION

In this section the Motivation and Background work done for the thesis, as well as our contribution and outline of the thesis are summarized.

1.1 Motivation for the work

Modern electronic devices require efficient, high quality, light weight power supplies. We have linear power regulators, whose principle of operation depends on current or voltage division which is inefficient. The main area of application is at low power levels. When it comes to high power levels switching regulators are used where switch operates in on and off states. Latest power electronic switches can operate at high frequencies. Therefore, faster dynamic response to rapid changes is the load current is possible with high operating frequencies. These High frequency electronic power processors are used in dc-dc power conversion.

The main functions of dc-dc converters are:

1. It converts DC input voltage into DC output voltage.
2. It provides isolation between source and load.
3. It can regulate the output voltage against load.
4. It can reduce the ac voltage ripple on the dc output voltage.

The dc-dc converters are mainly divided into two types:

1. Hard switching pulse width modulated (PWM) converters and
2. Resonant and soft switching converters.

In this thesis we deal with PWM dc to dc converters which are very popular for the last few decades and can be used at all power levels [1].

Some applications have additional technical constraints. Consider the power supplies used in battery powered electronics, such as laptop computers or mobile phones have a requirement of maintaining high efficiency over a wide range of loads. In desktop computers and servers, the microprocessor supplies must include the capabilities of digitally programmed output voltage. The output must depend on the load as well the dynamic response must be faster even for large load transients. Voltage Regulator Modules have multi phase architectures consisting of several buck or similar converter modules which operate in parallel to share the load current in order to improve dynamic response [2].

So because of the wide range of applications in industries, telecom sector and in medical field given rise to the development of "Digital Power" which leads to computerizing the DC to DC converters, hence the main focus of the DC to DC converters area today. We can obtain the better performance by modeling and simulation of the system. The modeling depends on the internal structure of the system and system dynamics are influenced by the load of the system. If we have insufficient information about the system parameters it cause to error in designing the controller. So, better control can be obtained by using experimental data to determine the load information [3].

System identification can be done in two ways, Parametric and Non-parametric identification. In Non-parametric method we use spectral analysis and correlation analysis to estimate frequency response or impulse response of the system. The behavior of the system is then estimated from the obtained frequency response. Where as in parametric estimation, a model structure is proposed and the parameter of the model is identified using information extracted from the system [4]. In this paper we are working with Non-parametric system identification method.

Many works have been done for simulating and load identification of buck converters. In [5] and [6] the design of simulink model for dc-dc buck converter is shown. In [6] and [7] few methods to identify load parameter of buck converter are proposed. In [8], the system frequency response is obtained by using non-parametric method by means of correlation analysis. This type of identification techniques requires long processing of data sequence. There is a need to propose few more simple methods to identify the load parameter of dc-dc buck converter.

1.2 Summary of Contribution

In this paper we have designed the simulink model of Ericson's BMR 450 model, where we considered capacitor as load. The simulink model is designed with the help of equations derived by applying Kirchhoff's laws to buck converter model. Here our target is to identify the load value by using some methods, where we proposed some simple methods.

The main contribution can be summarized as:

1. Designing the simulink model of buck converter.
2. Derived the equation useful to find the load value.
3. Plotted the frequency response of the simulink to get the resonant point that helps in calculating the load value.

1.3 Outline of the Thesis

The overall work is divided into 5 sections, where

Section 1: Gives you the detailed description of the thesis work as well the motivation for the thesis and background work done, and the contribution for the thesis.

Section 2: Gives you the detailed description of simple buck converter of Ericsson's BMR 450 model.

Section 3: Gives you the designing procedure of a simulink model with the help of equations derived from the buck converter.

Section 4: Gives you the methods which are proposed for identification of the load.

Section 5: Gives you the conclusion and future work for the work done in the thesis.

Buck Converter

2. BUCK CONVERTER

In this section we summarized the brief introduction of buck converter and purpose why we choose the buck converter as well the circuit topology and the brief explanation of the components used in the construction of buck converter.

2.1 Introduction

There has been an incredible development in the field of electrical components in recent years. The competition is to make things portable and flexible so that the usage will be more with less effort. As stated for electrical components to run, the power consumption is the major factor. For the optimum usage of electronic components, dc to dc converter plays a major role. The dc to dc converter can be used for many electronic components and it is widely used in telephone components and many other electronic devices. The purpose of dc to dc converter is to convert (i.e. to step down) the voltage from one value to the other and to perform regulation for the electronic circuit. Our main aim of the thesis is to identify the passive component that is the capacitive load using LMS and RLS algorithms in system identification procedure. Since we knew that there are high load variations in the output of the system, we need to identify the output load at every point and vary the input so that we can offer better self regulation in the system.

2.2 DC-DC Converters

The dc-dc converters are used to convert dc bus voltage to various other voltages based on the requirements of particular loads in building blocks of distributed power supply systems. This kind of systems is common in ships, airplanes space stations, telecommunication equipment and as well in computers. In modern wireless communication and signal processing systems will use variable supply voltages to minimize power consumption and to extend battery life [1].

In the field of power electronics, when power consumption factor is taken into consideration, a dc-dc buck converter is highly efficient for high load current changes. The processing of electrical power buck converter is a step down dc to dc converter or a step up boost converter. A buck converter acts like a switch mode power supply (SMPS). SMPS can achieve high energy efficiency and high voltage accuracy even it is non linear and discontinues in nature. A linear regulator can also be used in the place of a buck converter, but the energy dissipation is high for linear regulators, so to overcome this drawback we opt for buck converter.

2.3 Why Buck Converter?

In general the simplest way to reduce the voltage of a DC supply is by using linear regulators. Consider the linear regulator as shown in Figure 1. Here, the source voltage is V_S which is to be step down to voltage V_L across the resistor R_1 which means the voltage across R_L must be dropped which intern results in waste of power in the form of heat [6]. This problem can be overcome by using Buck Converter as it uses switch (Diode) to operate in ON and OFF states.

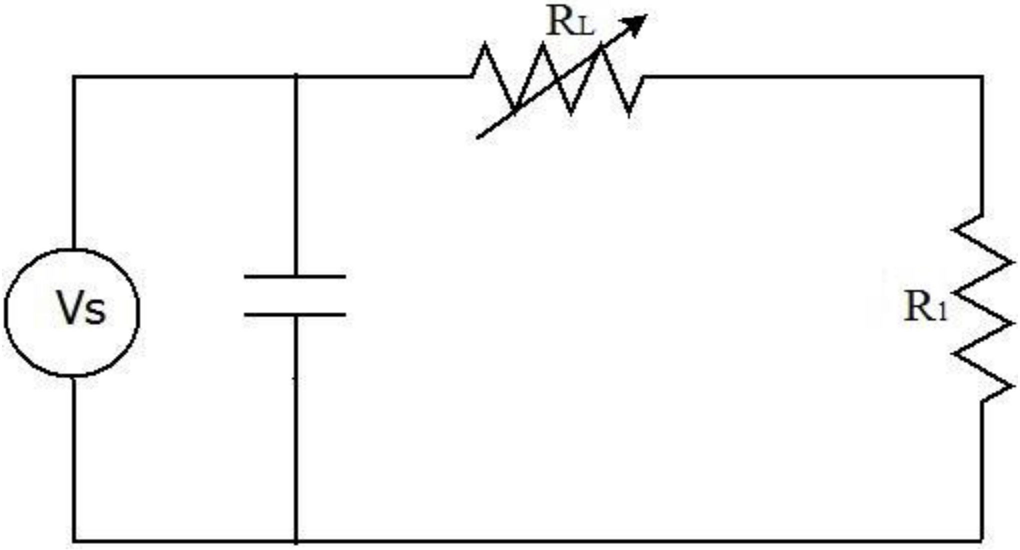


Figure 1. Circuit diagram of a Linear Regulator

The dc-dc buck converter topology is most widely used power management and microprocessor voltage-regulator applications. These applications require high frequency and transient response over a wide load current range. They can convert high voltage into low regulated voltage. Buck converter can be used in computers, where we need voltage to be stepped down. Buck converter provides long battery life for mobile phones which spend most of the time in stand-by state [9].

When the switch is ON the inductor gets charged to its maximum level, because of its flexibility of ON and OFF states it can be switched to OFF state when inductor charges to its maximum capacity. With this feature the usage of heat sinks and cooling agents can be avoided. Hence, because of its advantage we opt for buck converter rather than a linear regulator.

2.4 Buck Converter Circuit topology

The name “Buck Converter” itself indicates that the input voltage is bucked or attenuated and low voltage appears at the output. A buck converter or step down voltage regulator provides non isolated, switch mode dc-dc conversion with the advantage of simplicity and low cost [9]. Figure 2, shows a simplified dc-dc buck converter that accepts a dc input and uses pulse width modulation of switching frequency to control the output voltage. The buck converter consists of Source Voltage ‘V_S’, Diode, Inductor ‘L’, Inductor Resistance ‘R_L’, Capacitor ‘C’, and Capacitive Resistance ‘R_C’ all connected to a Load.

Switch mode power supply is generally used to provide the output voltage which is less than the input voltage to the load from an intermediate DC input voltage bus or a battery source. A simplified buck converter point of load which has power supply from a switch mode buck converter is shown in Figure.3. The buck converter consists of main power switch, a diode, a low-pass filter (L and C) and a load [2]. The basic buck converter operates in ON and OFF states. In ON state i.e. when the switch is closed the current to load is supplied from source voltage through inductor, where inductor gets charged to its peak level. Where as in OFF state i.e. when switch is open the inductor acts as source to the load.

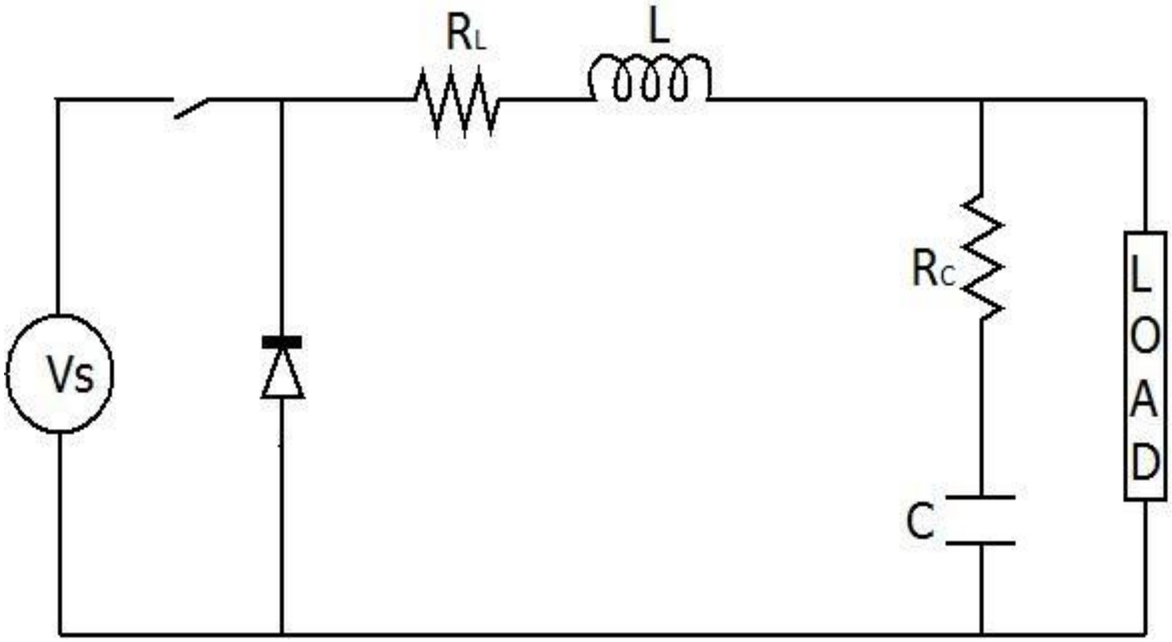


Figure 2. Buck Converter

Circuit components explanation:

2.4.1 Switch

Figure 3. Switch

Consider a switch as shown in Figure 3. We use transistor as a switch in buck converter, the input to the transistor is a pulse width modulated (PWM) signal which is used to turn ON or turn OFF the transistor. When the switch is turned ON the input voltage equals the load voltage and the voltage across the inductor, when the switch is turned OFF the load voltage equals the voltage across the inductor. The average output voltage can be controlled by varying the PWM signal [10].

2.4.2 Inductor

Figure 4. Inductor

Consider an inductor as shown in Figure 4. An inductor supplies constant power to the load resistor when the switch is turned OFF. It helps to maintain a continuous current across the load resistor when there is no supply voltage. It also controls sudden changes in the current when the switch is ON [10].

2.4.3 Capacitor

Figure 5. Capacitor

Consider a capacitor as shown in Figure 5. This acts as a low pass filter and removes harmonics in the output. It must be chosen large enough in accordance to control the voltage changes, overshoots, ripples during the time when the switch is changing on and off [10].

2.4.4 Resistor

Figure 6. Resistor

Consider a resistor as shown in Figure 6. A resistor is a component of an electrical circuit which helps to oppose the flow of electrons into the component. The flow of current through the resistor is inversely proportional to the value of the resistance [10].

2.4.5 Diode

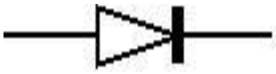


Figure 7. Diode

Consider a diode as shown in Figure 7. Diode is an electrical component which has two states of operation i.e. ON and OFF state. The ON and OFF states depends on the direction of flow of current through it. When the current flows from positive to negative terminal the diode acts as short circuit and allows the flow of current through it which is stated as ON state. When the current flows from negative to positive terminal the diode acts as open circuit and opposes the flow of current through it which is stated as OFF state [10].

2.5 Two States of operation of Buck Converter

2.5.1 On State

Figure 8, shows the buck converter operating in on state. In this state of operation the switch will be in closed state so that Vs will be the source voltage for the inductor. Obviously in this state the current through the diode flows from negative terminal to positive terminal which causes diode to be inactive. Hence there will be no backward current to the inductor.

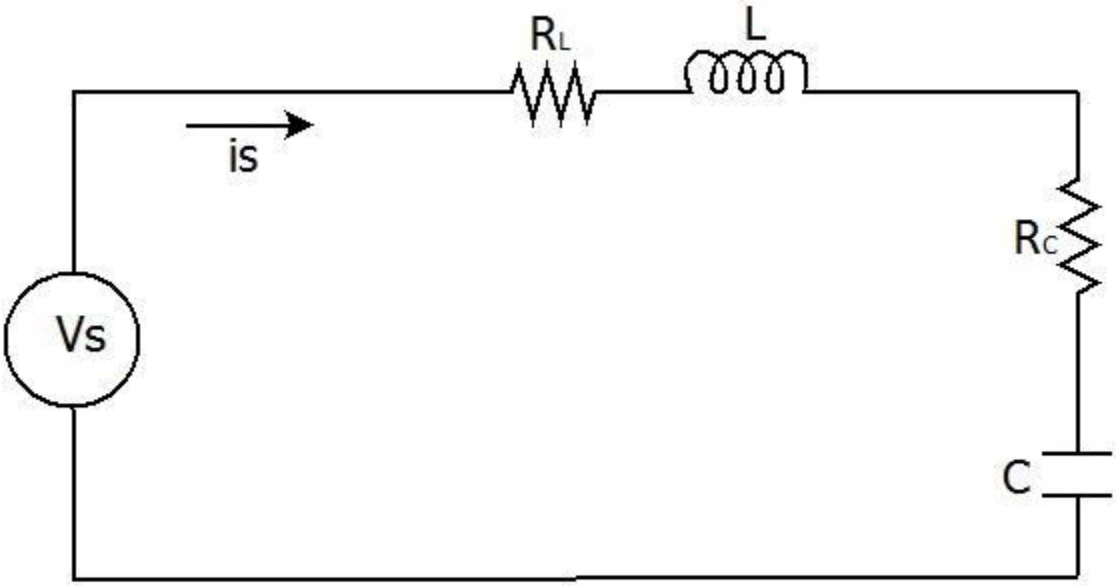


Figure 8. On State of Buck Converter

2.5.2 Off State

Figure 9, shows the buck converter operating in off state. In this state of operation the switch will be in open state so that there will be no path to current to flow from source voltage Vs to inductor. In this state inductor starts discharging, which cause current in diode to flow from positive to negative terminals. Hence there will be a backward current to the inductor.

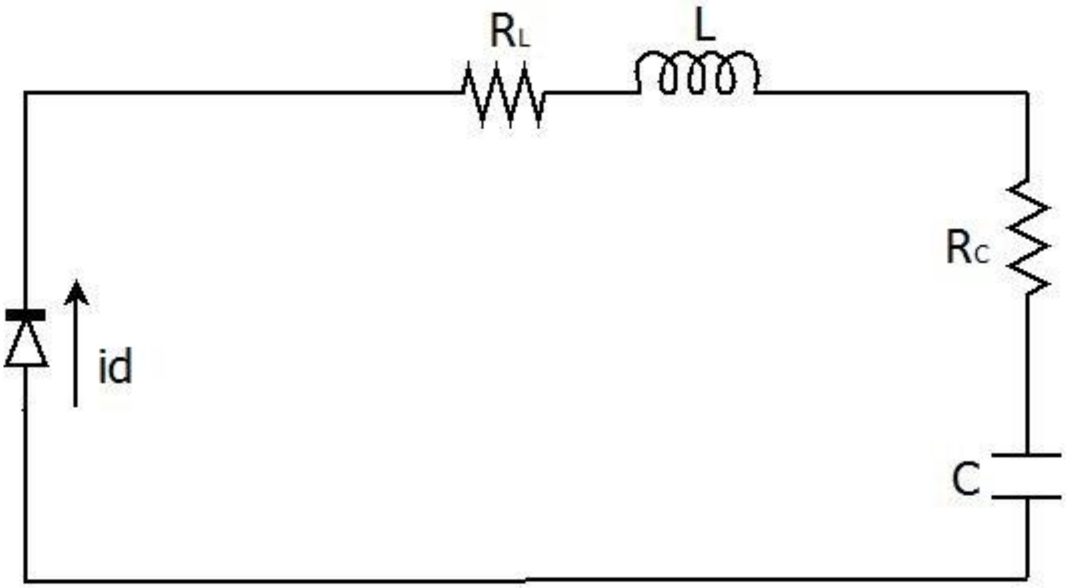


Figure 9. Off State of Buck Converter

Figure 10, shows the buck converter wave forms i.e. ‘VL’ shows the voltage across the inductor, ‘iS’ shows the switch modes during the time T and ‘iL’ shows the current flow during on and off states.

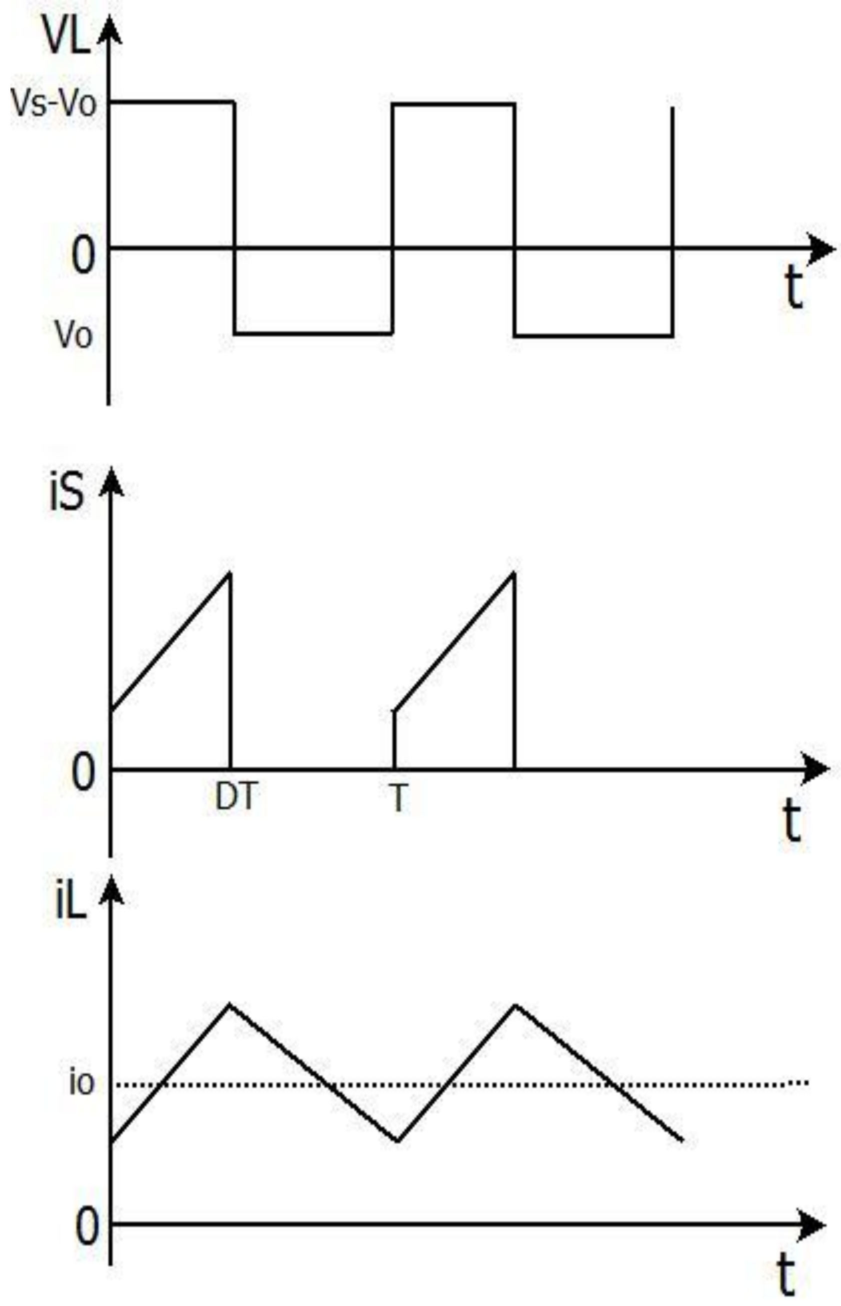


Figure 10. Buck converter wave forms

The relationship between input voltage, output voltage and the switch duty cycle ‘D’ can be derived from VL waveform. According to Faraday’s law, the inductor volt second product over a period of steady state operation is zero [1].

For the buck converter:

$$(V_s - V_o)DT = -V_o(1 - D)T$$

Where V_s : Source Voltage,
V_o : Output Vlotage,
T : Time period,
And D : Duty cycle.

Hence the dc voltage transfer function can be defined as the ratio of the output voltage to the input voltage,

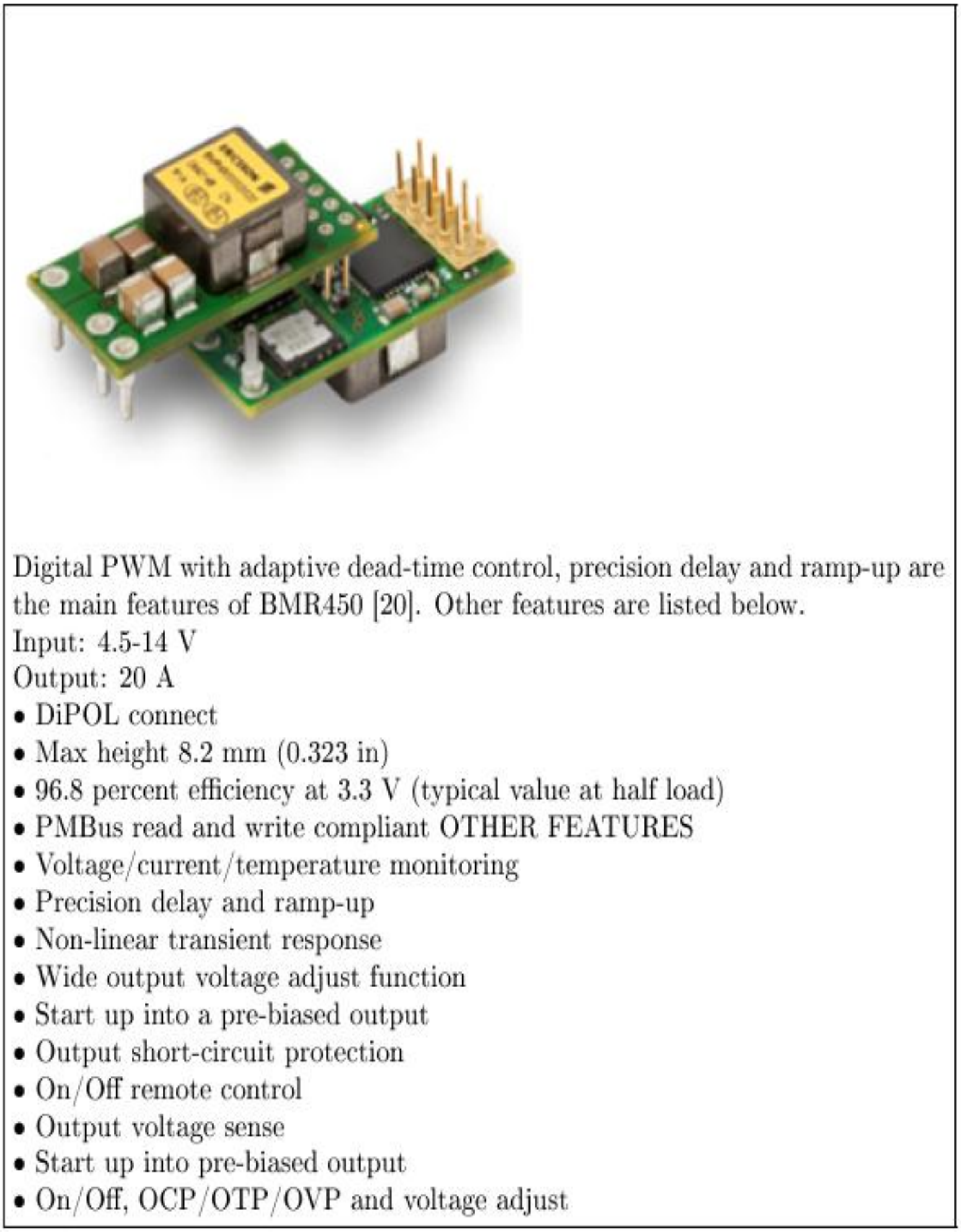
$$D = \frac{V_o}{V_s}$$

2.6 Modes of operation

Buck converter can operate in two modes of operation, Continuous mode and Discontinuous mode. In continuous mode, current at inductor never falls to zero. Where as in discontinuous mode at one point of time the current in inductor falls to zero due to consumption of energy by the load.

2.7 Ericsson’s BMR 450 features

Till now we have been using the general model now we move to the Ericsson BMR 450. In “Digital Power” BMR 450 is one of the first products developed by Ericsson. Researchers are going on to develop the methods used to identify the buck converter load properties. Using those properties the functionality, reliability and performance of the converters can be enhanced. The main features of the Ericsson BMR 450 are shown in Figure 11 [6].



Digital PWM with adaptive dead-time control, precision delay and ramp-up are the main features of BMR450 [20]. Other features are listed below.

Input: 4.5-14 V

Output: 20 A

- DiPOL connect
- Max height 8.2 mm (0.323 in)
- 96.8 percent efficiency at 3.3 V (typical value at half load)
- PMBus read and write compliant OTHER FEATURES
- Voltage/current/temperature monitoring
- Precision delay and ramp-up
- Non-linear transient response
- Wide output voltage adjust function
- Start up into a pre-biased output
- Output short-circuit protection
- On/Off remote control
- Output voltage sense
- Start up into pre-biased output
- On/Off, OCP/OTP/OVP and voltage adjust

Figure 11. BMR 450 Features

2.8 State space model of Buck converter

A DC-DC converter is a device which takes unregulated DC voltage as input and gives regulated DC voltage as output. The output voltage may be lower than the input, where the converter in this case is often known as buck converter, or the output voltage may be higher than the input, where the converter in this case is often known as boost converter, or the output voltage may be equal to the input. Here in this thesis work we are using buck converter. In switching buck converter we use semi conductors like BJT or FET as switching component which operates periodically with duty cycle'd'. The duty cycle'd' can be provided with the help of pulse width modulated (PWM) signal.

In general to describe a system, differential equations which are composed of transfer functions are interconnected, where each transfer function describes a subsystem. In most of the cases this is a very complicated task. This can be made simple by dealing this with state space model. State space model is the representation of the buck converter model with matrices. State space model can be analyzed easily just because of its matrix notation which can be easily implemented with the help of MATLAB. Moreover the state space models have flexibility to deal with multiple input and multiple output models [1].

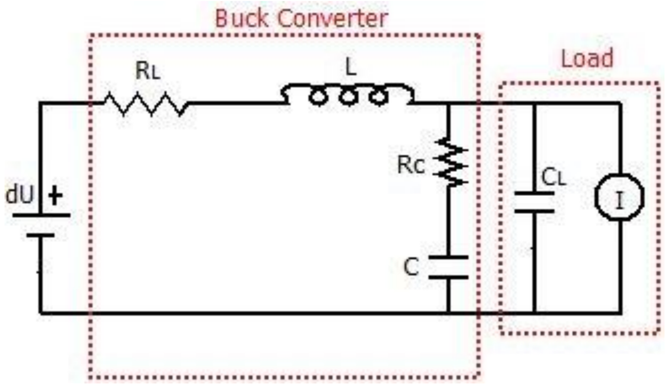


Figure 12. Buck Converter with Capacitive Load

Figure 12, shows the buck converter connected to a load, where we considered the load to be a capacitor in our thesis [6]. Now the buck converter is to be transformed into a state space model. The converter forms state vector 'x(t)', which is having independent state variables such as inductor current and voltages of capacitor and load. The converter is driven by the vector 'u(t)', which is formed by the independent sources. The output vector 'y(t)' consists of the dependent desired signals which are of our own interest [14].

Parameters for the Experimental model

Parameter Name	Value [Units]
dU	12 [V]
R_L	0.01[Ω]
L	0.9e-6[L]
R_C	0.01[Ω]
C	75e-6[C]
I	10e-3[I]

Our aim is to represent the above figured buck converter in the form of,

$$x(t) = Ax(t) + Bu(t) + Ke(t)$$
$$y(t) = Cx(t) + Du(t) + e(t)$$

Where x(t) state vector, u(t) input vector, y(t) the output vector and e(t) stochastic error.

Here A is an (n x n) matrix, where n represents the number of states.
B is an (n x m) matrix, where m is the number of inputs.
C is an (p x n) matrix, where p is number of outputs.
D is an (p x m) matrix.
K is the Kalman gain matrix.

The general structure of the dc-dc converter to be analyzed is shown in the above figure. It consists of inductor resistance RL and the converter capacitive equivalent series resistance R_C. Selecting suitable model is an important aspect in control systems, here we choose state space model for dc-dc converter which is the preferable efficient method for dynamic modeling. The model of the buck converter circuit can be obtained by applying Kirchhoff's voltage and Kirchhoff's current laws which results in set of equations helpful in designing the power circuit [1].

By applying Kirchhoff's Voltage Law to Figure 12 we get,

$$du = R_L i_l + L\frac{di_l}{d_t} + V_0$$

$$L\frac{di_l}{dt} = du - R_L i_l - V_0$$

$$\frac{di_l}{dt} = \frac{1}{L}(du - R_L i_l - V_0) \qquad (1)$$

$$C\frac{dV_c}{dt} = \frac{V_0 - V_c}{R_c}$$

Also $\frac{dV_c}{dt} = \frac{1}{C}\left(\frac{V_0 - V_c}{R_c}\right)$ (2)

Now by applying Kirchhoff's Current Law to Figure 13 we get,

$$i_l = \frac{V_0 - V_c}{R_c} + C_L\frac{dV_0}{dt} + i_0$$

$$C_L\frac{dV_0}{dt} = i_l - \frac{V_0 - V_c}{R_c} - i_0$$

$$\frac{dV_0}{dt} = \frac{1}{C_L}(i_l - \frac{V_0 - V_c}{R_c} - i_0) \qquad (3)$$

$$V_0 = V_{C_L} \qquad (4)$$

In Matrix form the above Equations (1), (2), (3) and (4) can be rearranged as,

$$\frac{d}{dt}\begin{bmatrix} i_l \\ V_c \\ V_{C_L} \end{bmatrix} = \begin{bmatrix} -\frac{R_L}{L} & 0 & -\frac{1}{L} \\ 0 & -\frac{1}{CR_C} & \frac{1}{CR_C} \\ \frac{1}{C_L} & \frac{1}{C_L R_C} & -\frac{1}{C_L R_C} \end{bmatrix} \begin{bmatrix} i_l \\ V_c \\ V_{C_L} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & 0 \\ 0 & -\frac{1}{C_L} \end{bmatrix} \begin{bmatrix} dU \\ i_0 \end{bmatrix}$$

$$V_0 = [0\ 0\ 1]\begin{bmatrix} i_l \\ V_c \\ V_{C_L} \end{bmatrix} + [0\ 0]\begin{bmatrix} dU \\ i_0 \end{bmatrix}$$

Simulink Model of Buck Converter

3. SIMULINK IMPLEMENTATION OF BUCK CONVERTER

In this section the brief explanation of simulink model as well as the designing procedure of simulink for the required Buck Converter and the input and output graphs are summarized.

3.1 Introduction

Simulink provides an environment for designing dynamic and embedded systems in multi-domain simulation and Model-Based Design. It provides a Graphical User Interface (GUI) which contains a set of block libraries which helps you in design, simulation, implementation and testing the various time-varying systems. These systems can be from any field such as communications, control systems, signal processing, video processing and image processing.

As Simulink is integrated with MATLAB, and can provide immediate access to vast range of tools it is easy to develop algorithms, analyze and can visualize the simulation results. We also can customize, can create batch processing scripts, and define signal, parameters and test data [7].

For simulating the buck converter we need to derive the equations that are useful to represent the buck converter in the simulink model. Those equations are represented in blocks which are formed by connecting the blocks provided by the simulink library. MATLAB’s ordinary differential equations (ODE) solver is used to determine the set of linear and non-linear differential equations. The simulation time and type of solver are set according to the data needed.

3.2 Simulink model of Buck Converter

The simulink model of buck converter is designed using the set of equations which represents the buck converter, where those equations can be obtained by applying the Kirchhoff’s Current and Voltage laws to buck converter.

The procedure for deriving the set of equations of buck converter is shown in the above section 2.8.

Hence the equations which give the behavior of the buck converter are listed as follows:

$$\frac{di_l}{dt} = \frac{1}{L}(du - R_l i_l - V_0)$$

$$\frac{dV_c}{dt} = \frac{1}{C}(\frac{V_0 - V_c}{R_c})$$

$$\frac{dV_0}{dt} = \frac{1}{C_L}(i_l - \frac{V_0 - V_c}{R_c} - i_0)$$

$$V_0 = V_{C_L}$$

By arranging these equations into blocks using MATLAB Simulink we have the simulink model of buck converter as shown in Figure 13 [6].

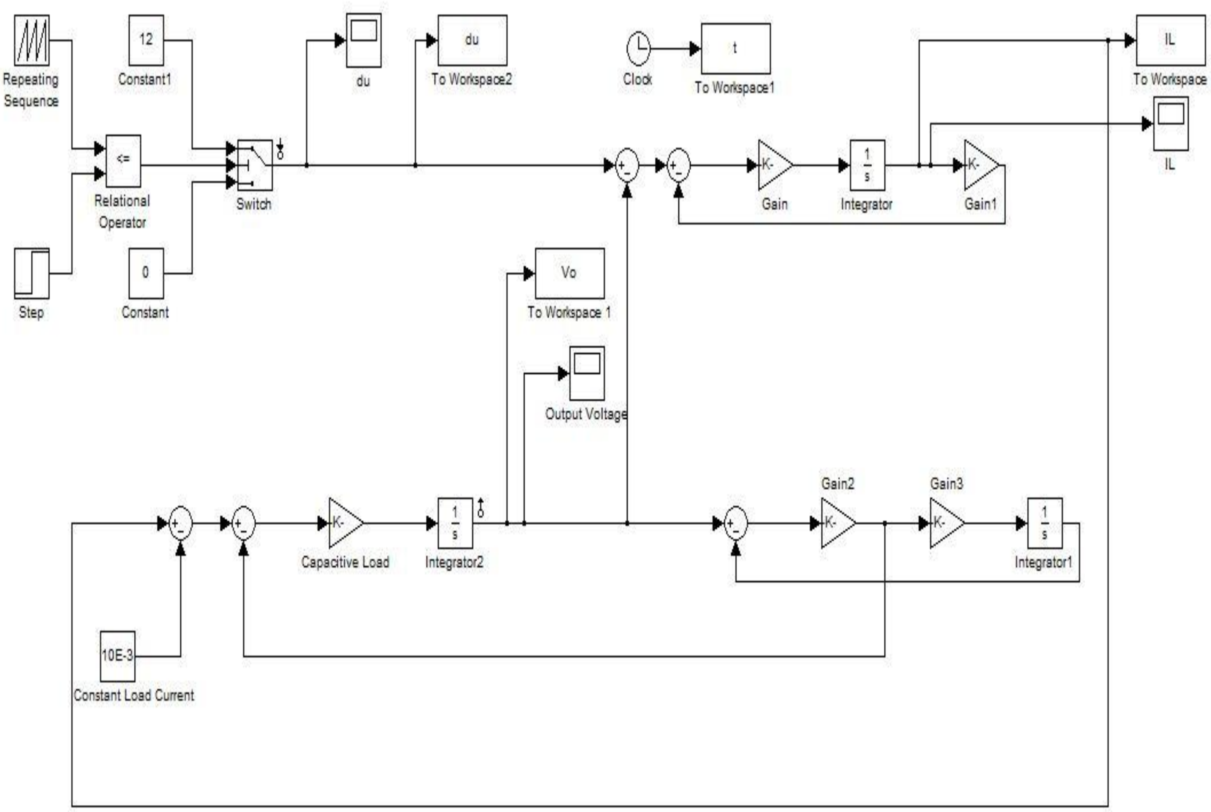


Figure 13. Simulink model of Buck Converter

The simulink model is mainly divided into three major parts, the pulse width modulator (PWM) i.e. the input generator, the buck converter model and the Load. The above simulink model shows the time domain representation of the buck converter in which the number of integers is equal to the number of state variables. It also consists of number of parameters such as capacitance ‘C’, the inductor ‘L’, the internal resistance of inductor ‘R_L’, the internal resistance of capacitor ‘R_C’ and the load capacitor ‘C_L’. Figure 14, shows the PWM signal generator [6].

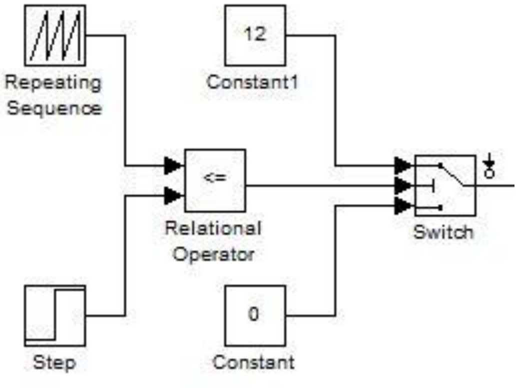


Figure 14. Generation of PWM signal

Here for the simulink we have two inputs, one of the input is the constant voltage source ‘dU’ which is controlled by duty cycle ‘d’. Where duty cycle can be defined as the ratio of the pulse width to switching period which have the values in the interval 0 to 1. The portion of the time period ‘Ts’ (Ts=1/Fs) is equal to ‘dTs’, when the switch is in On state, where‘d’ is the switch duty cycle. The steady state switch voltage is a periodic pulsating waveform has the amplitude approximately equal to the input voltage amplitude [2]. Figure.15 shows the pulse width modulator system which contains the Repeating sequence generator, Step signal generator, Relational operator, Constant generator and a Switch blocks. The maximum value of step response is equal to the duty cycle i.e. the output voltage divided by the input voltage. Now the switch control gives the output signal which is a continuous pulse having its maximum value 12v when the repeating sequence have the amplitude less than the amplitude of the step response and 0v when the repeating sequence have the amplitude less than the amplitude of the step response. Figure 16, shows the PWM signal generated by the block shown in Figure 15.

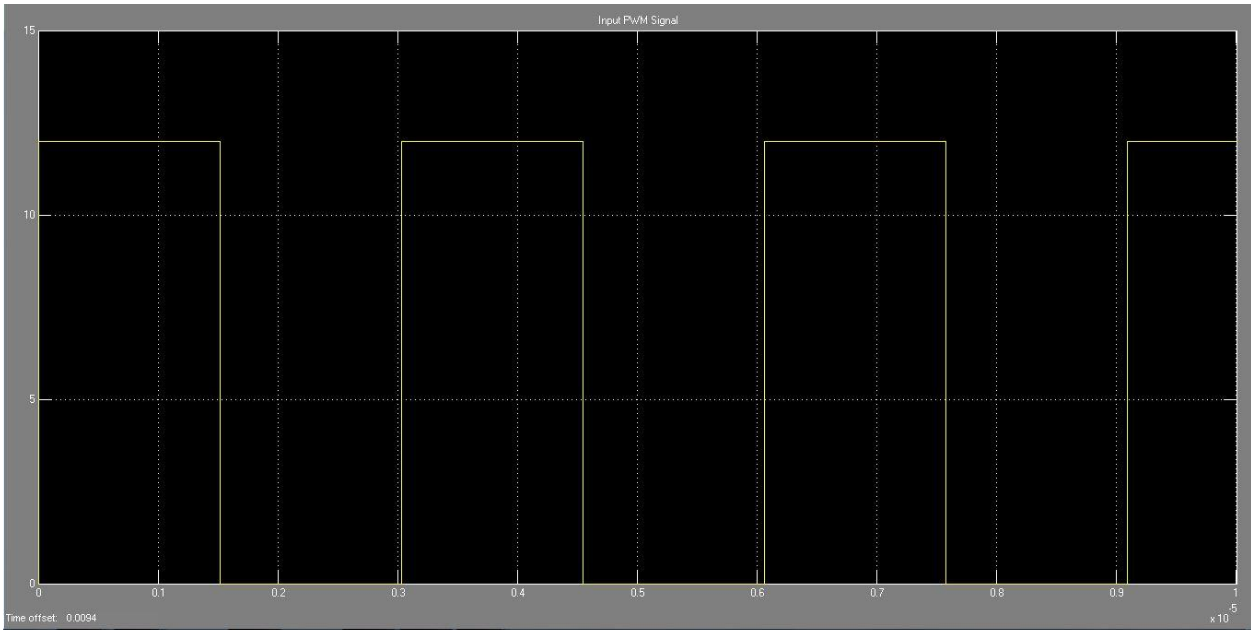


Figure 15. Simulation of PWM Input voltage

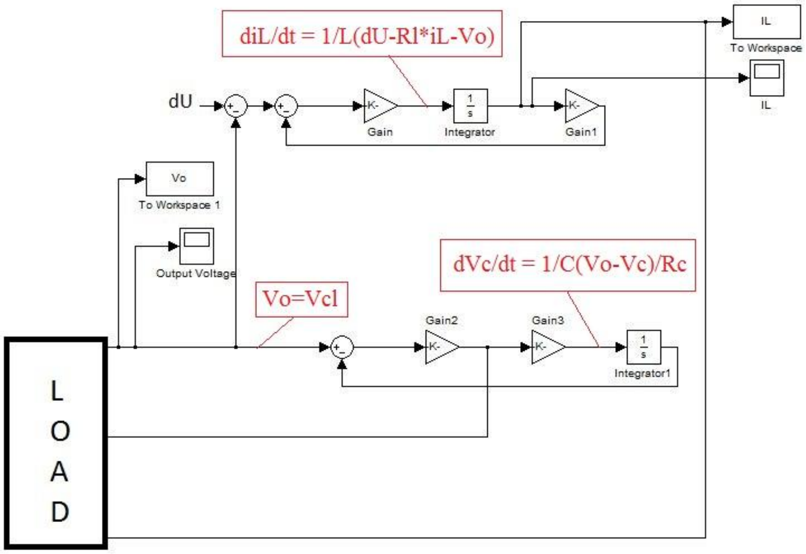


Figure 16**. Buck Converter model**

Figure 16, shows the buck converter model [6]. The buck converter model is designed using the available blocks in the simulink library, based on the equations derived from the buck converter. As input PWM signal is given to the buck converter and at the output load is connected. We are using capacitive load which is to be identified in our thesis.

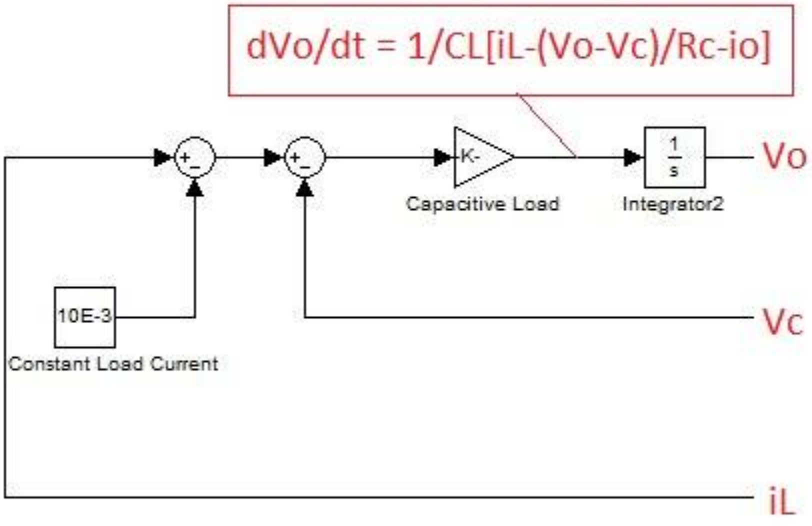


Figure 17. Load for Buck Converter

Figure 17, shows the Load constructed using blocks in simulink library [6]. Here we are using capacitor as load. Here we have another input which is a constant current provided by the load. By executing the whole simulink model the obtained output voltage is shown in Figure 18.

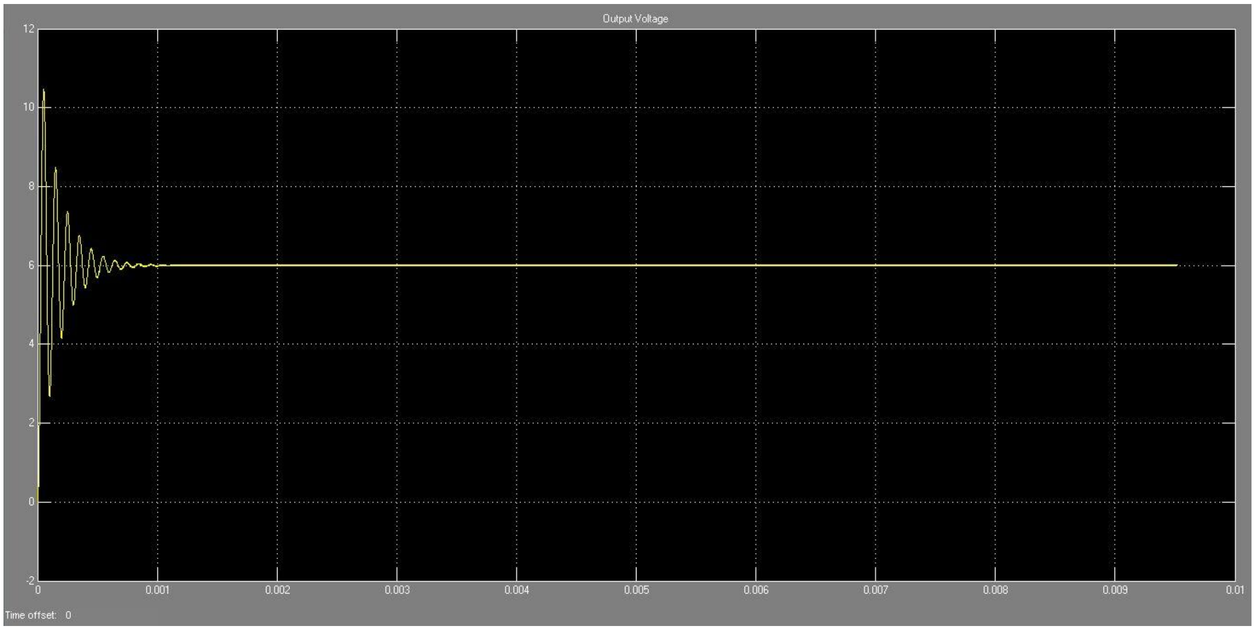


Figure 18. Simulation of Output voltage

3.3 Preparing Input and Output data

Significant information about the system in collected measurement is required for successful identification. This in turn requires well planned data acquisition. Regarding this several decisions have to be taken:

- *Choice of Input:* The input should excite the system. Pure sinusoid signal with frequency ω, gives information of the value of the frequency function at ω. If the system is nonlinear, an interval of the input that corresponds to the desired operation point should be chosen. In time domain, if we seek an input as a pulse train, consisting of pulses of different durations, it is of course not much use to have pulses so short that the response is hardly visible i.e. just covering a negligible part of the rise time of the step response. It is useful to have constant occasional pulses [9].

- *Choice of sampling interval:* The sampling interval is coupled to the time constant of the system. Sampling that is faster than the system dynamics leads to data redundancy. Whereas sampling that is slower than the system dynamics leads to serious difficulties in determining the dynamics parameters [9].

- *Post treatment of data:* In identification application we plot the data, and then we discover some deficiencies. It may be because some signal levels drift away or that there are high frequency disturbances above the frequency interval of interest. There may be some fault values in the data. To overcome these problems we need some post-treatment of data [9].

The load identification of the converter was performed by collecting data from the simulink model designed by equations derived from the buck converter. An input PWM signal is generated and corresponding output signal is obtained during the experiment. The data related to input and output signals are obtained as arrays to the workspace by its variable names where sampling frequency is 330 kHz. To main values were deducted from the data to remove the offset. This is an advantage to make a more accurate linear model due to the fact that the linear models are less responsive to slight deviation between input and output levels [11]. Figure 19, 20 and 21 shows Input signal, Output signal and Output signal with added White Noise correspondingly.

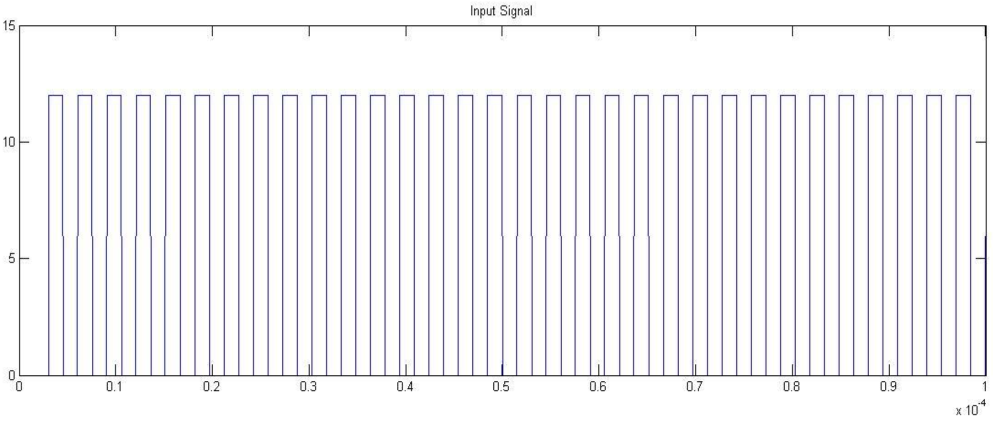


Figure 19. Input Signal

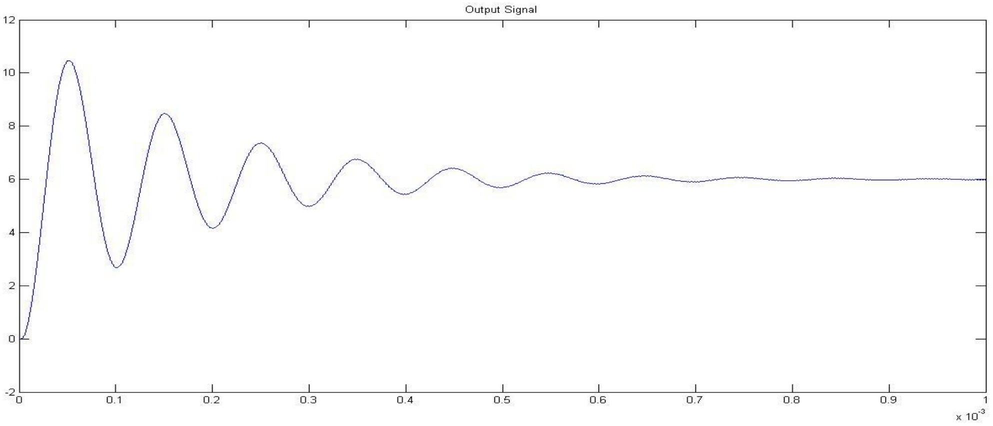


Figure 20. Output Signal

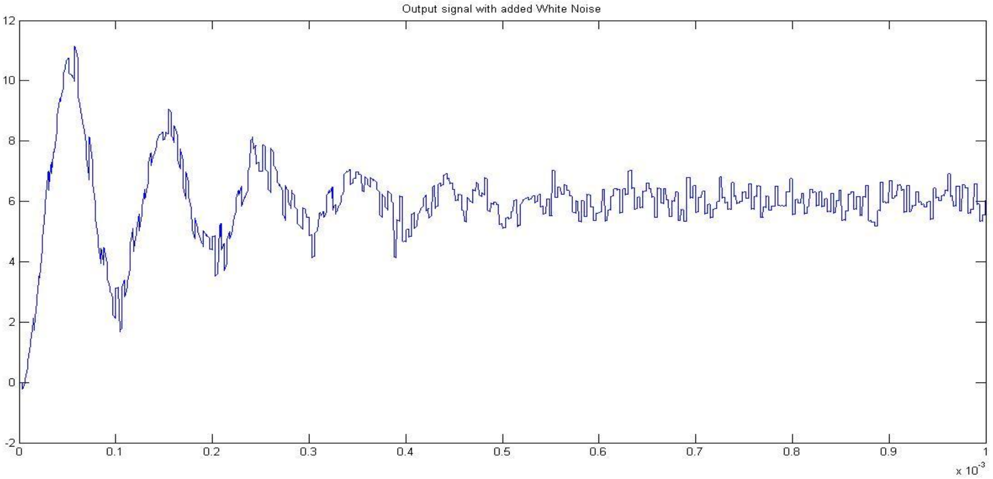


Figure 21. Output Signal with added White Noise

Load Identification

4. GENERAL METHODS TO IDENTIFY LOAD

In this section we summarize the methods which are useful to calculate the load capacitance value.

4.1 Method 1

In this method we have procedure, implementation and results of the proposed load identification method for dc to dc buck converter, where we find the load capacitance value by deriving the equation from the buck converter.

4.1.1 Procedure

In this method, initially since the capacitors in the low pass filter i.e. C1 and the load capacitance i.e. C2 are parallel we combine into single capacitor at the output of buck converter. Then, the equation for output voltage across the capacitor is taken into consideration, and change in voltage across inductor during on and off states of buck converter. Finally, obtained equations for on and off times are clubbed to get the equation for change in current for the total time period 'T'. Hence by rearranging the equation we get the final equation for capacitance value. Therefore, by substituting all the constant and variable values obtained from the simulink model we can obtain the load capacitance value.

4.1.2 Implementation

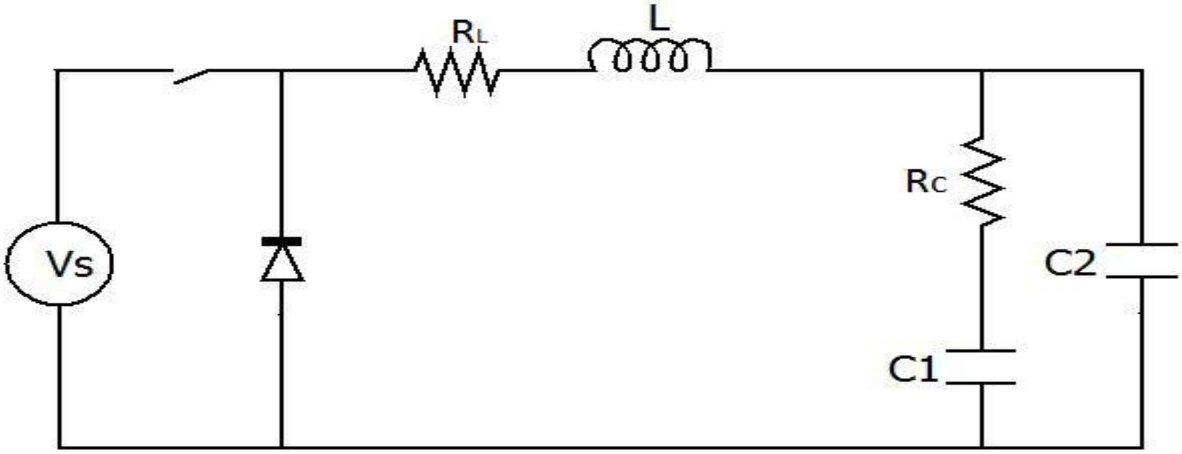


Figure 22. General Model of Buck Converter

Consider the Buck converter model shown in Figure 22. From that we can observe that C1 and C2 are in parallel. When two capacitors are connected in parallel the equivalent capacitance will be equal to the sum of the individual capacitors.

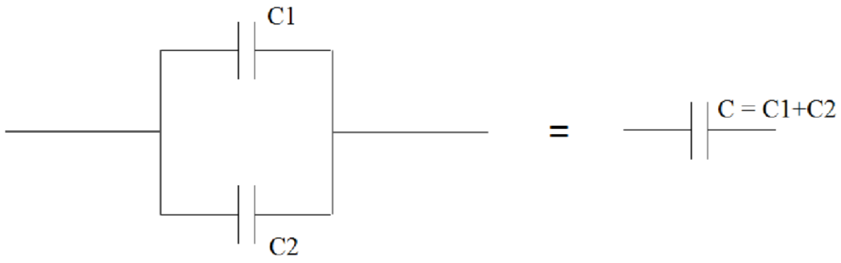


Figure 23. Equivalent capacitance of two parallel capacitors

By substituting the equivalent capacitance in the buck converter, Figure 22 can be rearranged as Figure 24 as shown below.

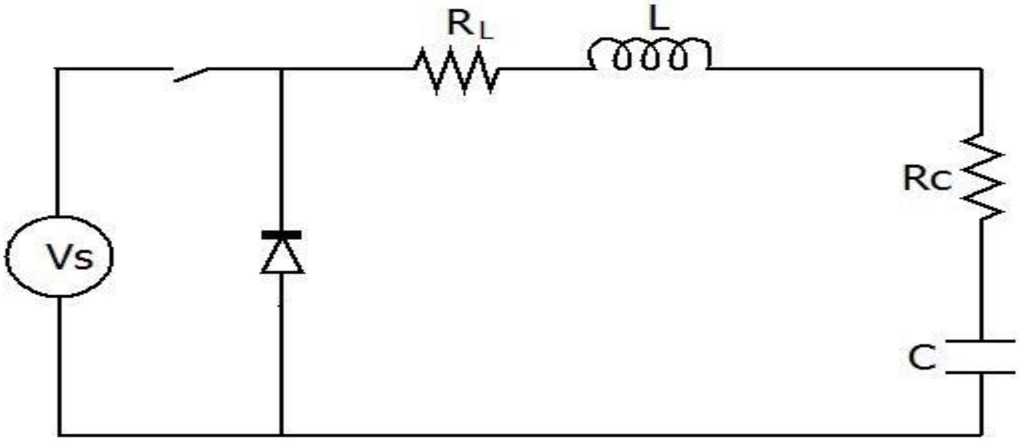


Figure 24. Transformed Buck Converter

Expression for change in voltage across capacitor can be give as,

$$\Delta Vout = 1/c \int ic \ dt$$

Average capacitive current which flows into $\frac{t_1}{2} + \frac{t_2}{2} = \frac{T}{2}$ is $ic = \Delta I/4$

We have $\Delta Vout = 1/c \int_0^{T/2} \Delta I/4 \ dt$

This implies,

$$\Delta Vout = \frac{\Delta I * T}{8C}$$

Since, $T = Ton + Toff$

Now deriving equations for Ton and $Toff$:

Change in voltage across inductor during time Ton:

$$Vin - Vout = \frac{L * \Delta I}{Ton}$$

This implies,

$$Ton = \frac{L * \Delta I}{Vin - Vout}$$

Change in voltage across inductor during time Toff :

$$0 - Vout = \frac{-\Delta I * L}{Toff}$$

This implies,

$$Toff = \frac{L * \Delta I}{Vout}$$

For total time $T = Ton + Toff = \frac{L*\Delta I}{Vin-Vout} + L * \frac{\Delta I}{Vout}$

This implies,

$$\Delta I = \frac{T * Vout * (Vin - Vout)}{L * Vin}$$

Substituting ΔI in $\Delta Vout$ we get

$$C = \frac{Vout(Vin - Vout)}{L * Vin * 8 * f^2 * \Delta Vout}$$

4.1.3 Results

We substitute all the constant and variable values obtained from the simulink in the derived equation to find the load capacitance value. Figure 25, shows the output voltage of the simulink model of a dc-dc buck converter.

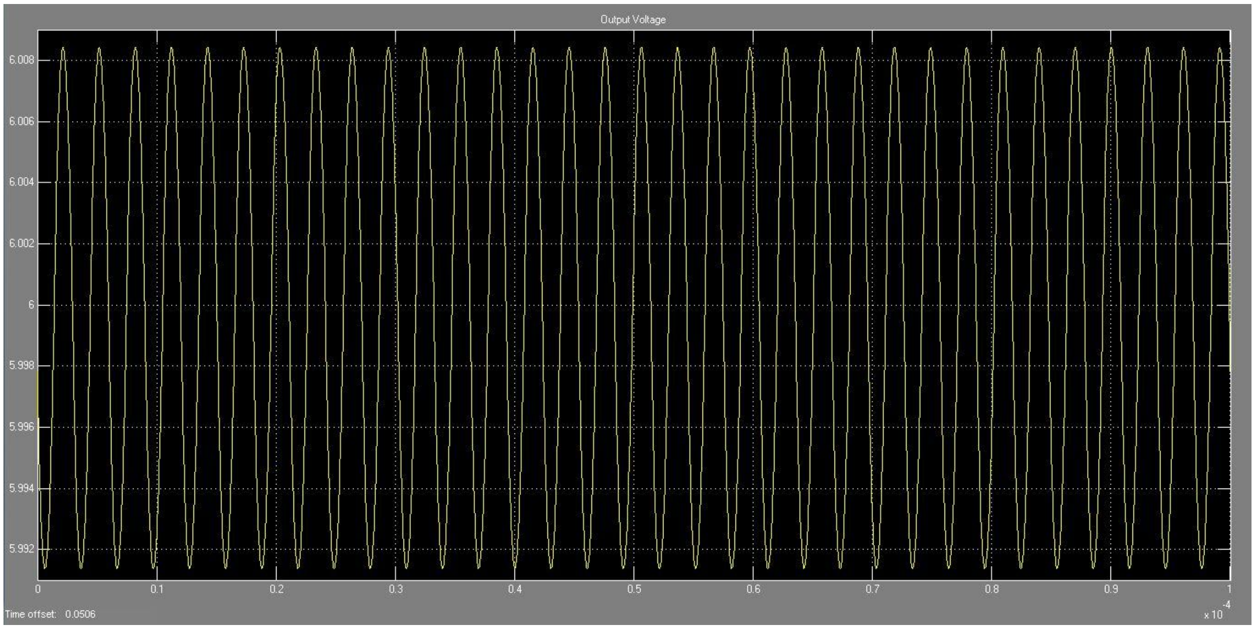


Figure 25. Output voltage of Buck Converter

$$\text{We have } C = \frac{Vout(Vin - Vout)}{L * Vin * 8 * f^2 * \Delta Vout}$$

$$V_{in} = 12v$$

$$V_{out} = \frac{6.008 + 5.992}{2} = 6v$$

$$L = 0.9e - 6$$

$$f = 330e^3$$

From the figure, $\Delta V_{out} = 6.001 - 5.9992 = 1.8e - 3$

By substituting the values and solving for C, We get $C = 2625\mu f$

We have $C = C_1 + C_2$

Since we know $C_1 = 75\mu f$ solving for C_2,

We get $C_2 = 2550\mu f$

Calculating and tabulating the % of error values:

$$\text{We have } \%\ of\ error = \frac{Estimated - Original}{Original} \times 100\ \%$$

$$\%\ of\ error = \frac{2550 - 2000}{2000} \times 100\ \%$$

$$Therefore, \%\ of\ error = 27.53\ \%$$

Similarly calculating for different values of C2 and tabulating we have the following table.

No.	C2 Original in µf	C2 Estimated in µf	% of Error
1.	200	239.13	19.5
2.	400	478.26	19.56
3.	800	956	19.56
4.	1500	1913	27.5
5.	2000	2550	27.53

Now by adding some White Noise at the output signal the Output voltage of Buck Converter simulink model is shown in Figure 26.

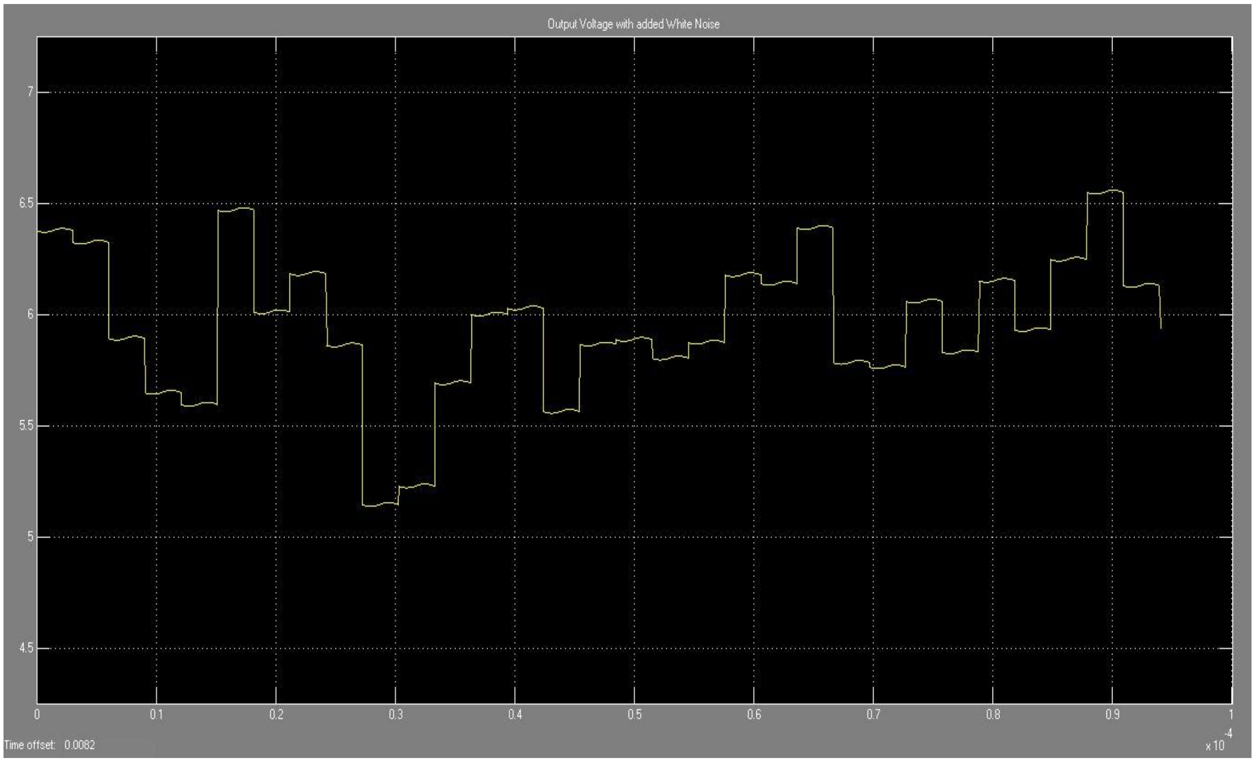


Figure 26. Output Voltage of Buck Converter

From the Figure 26, we can observe that the peak to peak voltage is not unique. So it is difficult to get parameters of the derived equation when we have noise in the input. Hence this method is not efficient for noisy systems.

4.2 Method 2

In this method we have procedure, implementation and results of the proposed load identification method for dc to dc buck converter. Here we find the load capacitance value by substituting the resonant point value obtained by bode plotting the response of buck converter using Linearization method.

4.2.1 Procedure

Initially we design simulink model of buck converter as shown in simulink section. Then, by using some MATLAB functions we plot the bode plot of the simulink model. In the bode plot we take the peak point value which is known as resonant point where the system have tendency to oscillate with maximum frequency. Finally, the peak value is substituted in resonant angular frequency ‘ω’ to get the load capacitance value.

4.2.2 Implementation

Here in our thesis we are going to find the load capacitor value by finding the resonance point of a bode plot. The bode plot of the simulink is obtained by using the falloing MATLAB functions.

Lin = Linearize(‘sys’,op,io)

The LINEARIZE function takes the simulink name i.e sys, operating point op and input output vector io as objects and returns a state-space model which is linear and time invariant, Lin. OPERPOINT or FINDOP functions are used to create operating point object op. Here we are choosing FINDOP to create operating point object. The linearized input or output object is obtained using the function GETLINIO. Now these required functions are explained in detail [11].

Op = findop(‘sys’,op_spec)

The “findop( )” function finds the operating point from the simulink. This function contains two arguments one of it helps to take simulink model and the other is an operating point specification object. This op_spec object can be created using OPERSPEC function. The operating point specifications such as minimum and maximum values, known values and initial guesses are specified by editing op-spec directly or by using get and set functions [11].

Op_spec = operspec(mdl)

The OPERSPEC function creates operating point specifications for simulink model ‘mdl’. This function returns an operating point specification object op_spec for a simulink model ‘mdl’ [11].

io = getlinio(‘sys’)

This function helps to find all linear inputs and outputs of a simulink and returns a vector of object io. Before running this function we need to set input and output points in the simulink from where this function gets the input and output signals information [11].

Bodeplot(lin)

This function plots bode magnitude and phase of the system model. The frequency range and number of points are chosen automatically [11].

4.2.3 Results

By implementing all the above discussed functions in MATLAB we get the bode plot of simulink model as shown in Figure 27.

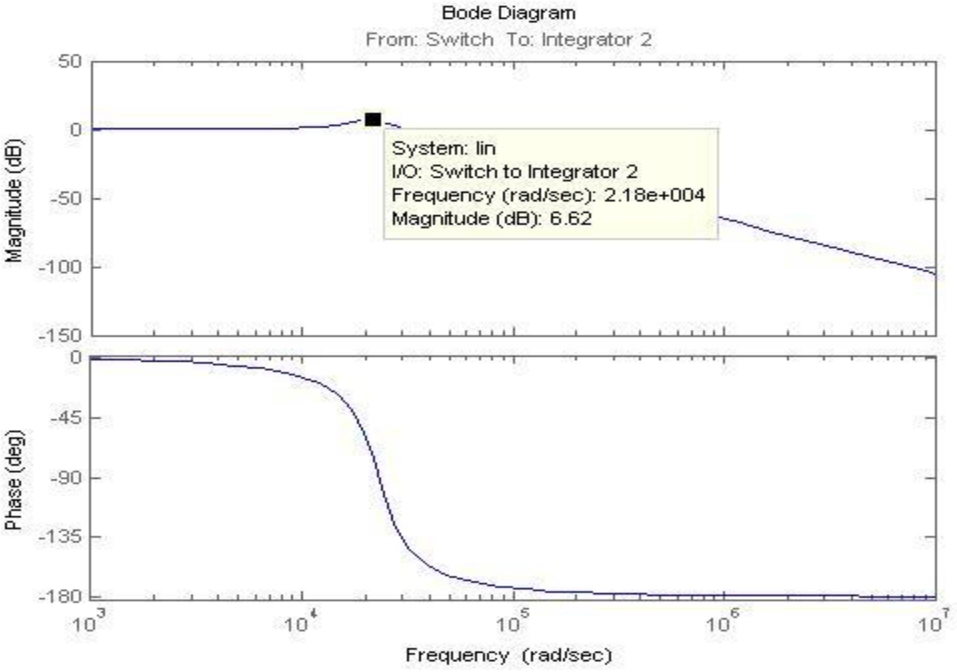


Figure 27. Bode plot diagram of State Space model.

Now by adding some White Noise to the output of simulink model and implementing we get the bode plot of simulink model as shown in Figure 28.

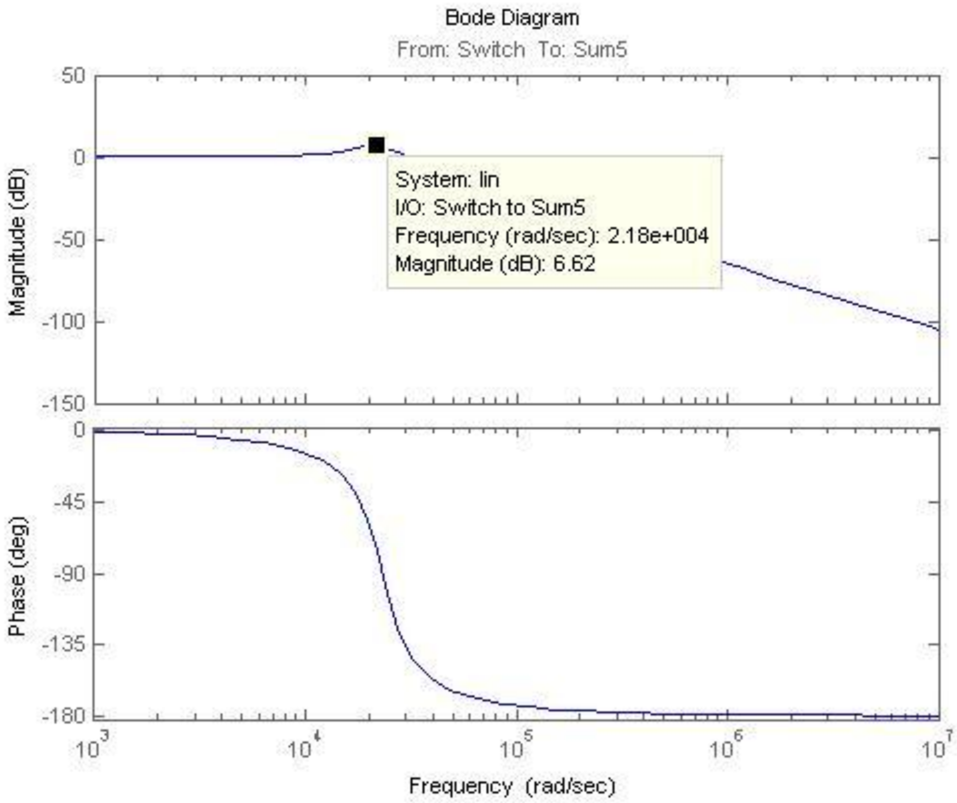


Figure 28. Bode plot diagram of a State space model with noise in the output.

When we plot the frequency response of a system, at some point we get the maximum value where the system has a tendency to oscillate with maximum frequency. From Figure 27, we can choose the value where the gain is high i.e. 'ω'=2.18e4 rad/sec.

In both the cases i.e. with and without noise at output, doesn't affect the value of resonant angular frequency value i.e. 'ω'=2.18e4 rad/sec.

We have expression for resonant angular frequency in an LC circuit as:

$$\omega = \frac{1}{sqrt\left(L(C_1 + C_2)\right)}$$

We can obtain the estimated load capacitance value by substituting all known values in the above expression.

Consider C2=2000µf, now calculating the value of C2 theoretically and comparing the obtained value with original value we get the % of error.

From the above Bode plot we have 'ω'=2.38e4 rad/sec,

$$\omega = \frac{1}{sqrt\left(L(C_1 + C_2)\right)}$$

$$C_2 = \frac{1}{L\omega^2} - C_1$$

$$C_2 = \frac{1}{0.9e - 6((2.18e^4)^2)} - 75e^{-6}$$

$$C_2 = 2337e^{-6} - 75e^{-6}$$

$$Therefore, C_2 = 2262\text{µf}$$

The problem with this type of model's is that due to the presence of some noises in the circuit and due to the presence of E.S.R (Equivalent Series Resistance) there may be some error in calculation of the capacitor value which causes the error with the original value we used in the buck converter.

Calculating and tabulating the % of error values:

We have $\% \ of \ Error = \frac{Original - Estimated}{Original} \times 100 \ \%$

$$\% \ of \ Error = \frac{2262 - 2000}{2000} \times 100 \ \%$$

$$Therefore, \% \ of \ Error = 13 \ \%$$

Similarly calculating for different values of C2 in both the cases i.e. with and without noise at the output and tabulating we have the following table:

No.	**C2 Original in µf**	**C2 Estimated in µf**	**% of Error**
1.	200	204	2
2.	400	357	10
3.	800	847	5
4.	1500	1362	9
5.	2000	2262	13

4.3 Method 3

In this method we have procedure, implementation and results of the proposed load identification method for dc to dc buck converter. Here we find the load capacitance value by substituting the resonant point value obtained by plotting the frequency response of transfer function of a simulink modeled buck converter.

4.3.1 Procedure

Initially we design simulink model of buck converter as shown in simulink section. Then, by using some MATLAB functions we get the transfer function of simulink model and plot the frequency response of the transfer function. In the plot we take the peak point value which is known as resonant point where the system have tendency to oscillate with maximum frequency. Finally, the peak value is substituted in resonant angular frequency 'ω' to get the load capacitance value.

4.3.2 Implementation

Here in our thesis we are going to find the load capacitance value by finding the resonance point of a frequency plot. The frequency plot of the simulink is obtained by using the fallowing MATLAB functions.

etfe (data,M)

In order to estimate the transfer function of the system, ETFE is used. The function ETFE is acronym of empirical transfer function estimation. It estimates the transfer function using Fourier analysis. The function synopsis of the ETFE is f=etfe (z.M,N,T). Z contains the input-output data [y u] or a time series y. Only single (or no) input systems can be handled. If an input is present G is returned as the ETFE (the ratio of the output Fourier transform to the input Fourier transform) for the data. For a time series G is returned as the periodogram (the normed absolute square of the Fourier transform) of the data. G is returned in the standard frequency function format. with M specified, a smoothing operation is performed on the raw spectral estimates.

The transfer function is estimated at 128 equally spaced frequencies between 0 (excluded) and pi. This number can be changed to N (a power of two) and the sampling interval can be changed from 1 (default) to T by G = ETFE(Z,M,N,T). This can also be interpreted as the spectral analysis estimate for a window size that is equal to the data length. For time series, 'etfe' gives the periodogram as a spectral estimate. The function also allows some smoothing of the crude estimate, it can be a good alternative for signals and systems with sharp resonances.

For input-output data: In this method the ratio of Fourier transform of input to Fourier transform of output is computed.

For time series data: In this method normalized absolute squares of the Fourier transform of the time series periodogram is computed.

This command works well for highly resonant systems. It also works well for periodic inputs and compute exact estimates at multiples of the fundamental frequency of the input and their ratio.

While computing the frequency resolution using the etfe command the following equation is used.

Frequency resolution= $2\pi/M$ (radians/ sampling interval)

Where, M is the scalar integer that sets the size of the lag window. The value of M controls the trade-off between bias and variance in the spectral estimate. The default value of M gives the maximum resolution. A large value of M gives good resolution but results in more uncertain estimates. If a true frequency function has a sharp peak, higher values of M are to be specified.

For a periodic input the frequency resolution can be known as follows. If the input data is marked as periodic and contains an integer number of periods, etfe computes the frequency response at frequencies $2\pi K/T$ (k/period) where K =1, 2, ……., period. For a periodic signal the frequency resolution is ignored. Although there are many techniques for estimating the transfer function, because of given data limitations they may yield poor results. One such method is empirical transfer function estimation, which estimates the transfer function by taking the ratios of the Fourier transform of the output y(t) and the input u(t). The estimate is given by
$G(w) = F(y(t))/F(u(t))$

If the data is noisy, the resulting estimate is also noisy. Unfortunately, taking more data points does not help. The variance does not decrease as the number of data points increase because there is no feature of information compression. There are as many independent estimates as there are data points.

ffplot (M)

This function plots the response of frequency function or spectrum. Where, the frequency units are Hz. Here ‘M’ is an estimation routine ‘etfe’ [11].

4.3.3 Results

By implementing all the above discussed functions in MATLAB we get the bode plot of simulink model as shown in Figure 29.

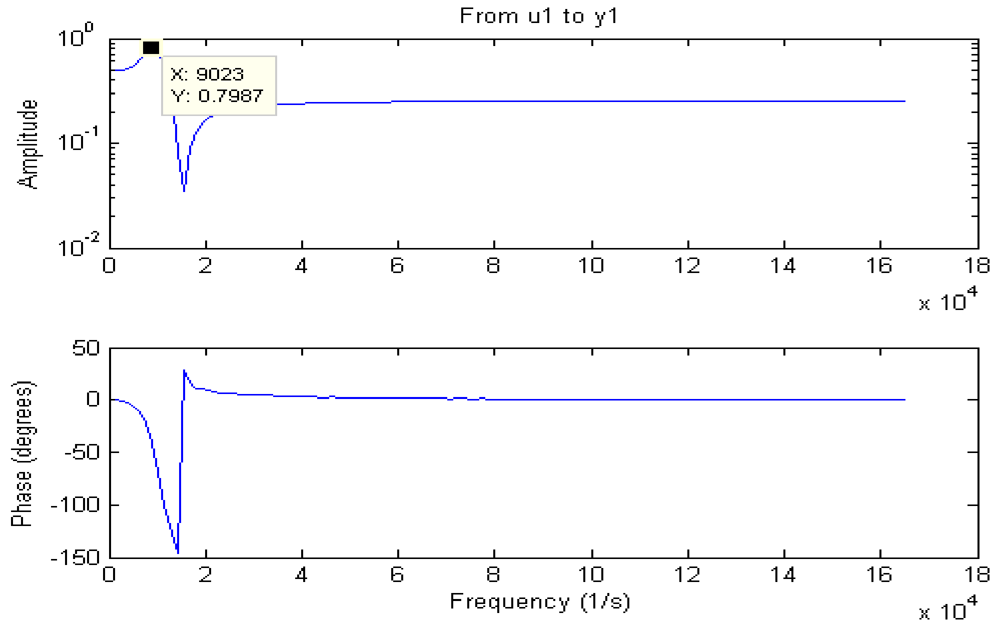


Figure 29. Frequency response of Buck Converter.

Now by adding some White Noise to the output of simulink model and implementing we get the bode plot of simulink model as shown in Figure 30.

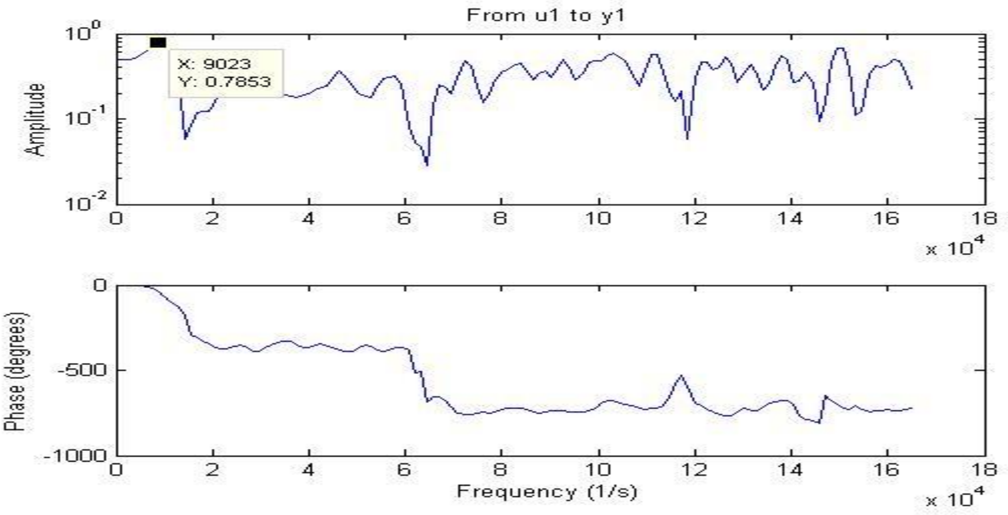


Figure 30. Frequency response of Buck Converter with Noise at the output.

When we plot the frequency response of a system, at some point we get the maximum value where the system has a tendency to oscillate with maximum frequency. From the above figures, we can choose the value where the gain is high i.e. 'f=9023(1/sec)'.

In both the cases i.e. with and without noise at output, doesn't effect the value of resonant frequency value i.e. 'f=9023(1/sec)'.

Consider C2=200µf, now calculating the value of C2 theoretically and comparing the obtained value with original value we get the % of error.

From the above frequency plot we have 'f=9023',

$$\text{We know } f = \frac{1}{2*\pi*sqrt\left(L(C_1+C_2)\right)}$$

$$C_2 = \frac{1}{Lw^2} - C_1$$

$$C_2 = \frac{1}{0.9e-6((2*\pi*9023)^2)} - 75e^{-6}$$

$$C_2 = 345e^{-6} - 75e^{-6}$$

$$Therefore, C_2 = 270\text{µf}$$

The problem with this type of model's is that due to the presence of some noises in the circuit and due to the presence of E.S.R (Equivalent Series Resistance) there may be some error in calculation of the capacitor value which causes the error with the original value we used in the buck converter.

Calculating and tabulating the % of error values:

$$\text{Now } \%\, of\ Error = \frac{Original-Estimated}{Original} \times 100\,\%$$

$$\%\, of\ Error = \frac{200-270}{200} \times 100\,\%$$

$$Therefore, \%\, of\ Error = 35\,\%$$

Similarly calculating for different values of C2 and tabulating we have the following table:

No.	**C2 Original in µf**	**C2 Estimated in µf**	**% of Error**
1.	200	270	35
2.	400	602	50
3.	800	983	22
4.	1500	1807	20
5.	2000	4159	107

Conclusion and Future Work

5. CONCLUSION AND FUTURE WORK

5.1 Conclusion

This thesis work describes three methods to identify the load value of a dc-dc buck converter model. These three methods work well for online approach and nonparametric way of estimating the capacitive load. At first we designed simulink model of buck convertor, then we designed two methods. In the first method we bought an equation to the capacitor directly with respect to the output voltage that is voltage across the capacitor. In the second method we divided Fourier transform of the output voltage and Fourier transform of the input voltage then we plotted the frequency response of the system from the result of the above division with different frequencies. As the system is having tank circuit that is inductor and capacitor are in series so the frequency response should have maximum value at resonance point, we have taken frequency point at that maximum value and we bought the capacitor value with some equation we derived. Proposed three methods perform well since we obtained very less percentage of error values. When there is some noise in the system output, the first method cannot be performed since the derived equation contains a parameter that cannot be predicted. Whereas second and third methods even perform well for noisy output.
Hence, in over all the proposed methods are helpful in finding a capacitive load of a dc-dc buck converter.

5.2 Future work

- Some online approach with more accuracy in finding the critical load capacitance with less time will be the best method.

- Equation that is helpful to find the load capacitance even in the presence of noise in the output will give better result.

- In the proposed methods, we used a capacitive load. Methods are to be proposed for a more complex load.

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