

Dynamic Modelling and Simulation of DC-DC Converters

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ABSTRACT

The DC-DC converter is an electrical circuit that transfers energy from a dc source to an electrical load. [1] The energy is first transferred into the energy storage elements by using the electronic switches, and then afterwards from the storage elements to the load. The storage elements are inductors and capacitors. [2] The transient analysis of the converters is important to see the dynamic performance of the circuit. The simulations are to be performed to observe the effects of the values of inductor and capacitor on the dynamic performance of the converters. To facilitate the simulation process, the differential equations are formulated into the state-space model of the circuit. The DC-DC converter has the special distinction of being a system of variable structure, that is, the circuit topology changes in accordance with the switching action of the semiconductor devices. The state-space model, therefore, must describe the dynamic behavior of the circuit for each portion of the switching cycle. In this project, the MATLAB software will be used for the state-space model simulation of the converters to see the dynamic performance of the converters in the continuous conduction mode (CCM) and discontinuous conduction mode (DCM).

Chapter 1 Introduction

DC-DC converters convert DC voltage to desired output level. Furthermore, they provide regulation as they keep the output voltage value constant even when input current and voltage values vary. [3] The desired output should be achieved with high efficiency. For power loss to be minimal the transistor is operated in switched state. Buck, Boost and Buck-Boost are three basic converters. Buck converter lowers the input voltage than the output voltage. Boost converter increases the output voltage than the input voltage. The buck-boost converter increases/decreases the input voltage than the output voltage. In this project we operate the converters in two modes- CCM(Continuous Conduction mode) and DCM(Discontinuous Conduction Mode). The inductor current never falls to zero or negative. It is always positive. In Discontinuous Conduction mode, when capacitance value is less than CCM capacitance value, the inductor current stays positive during switching cycle but becomes zero at the end of the switching cycle. After obtaining the inductance and capacitance values from CCM and DCM equations, these values are used in simulation to observe the simulation of converter under transient conditions. We use State space model for approximation of the time variant system of converter to time invariant system. We use Matlab for simulation of the model as it has function files that compute numerical solutions from coupled differential equations [4]

1.1 Methodology:

1.1.1 State Space Modelling:

The converter acts as time invariant system due to switching cycle when switching cycle is ON and when switching cycle is OFF, different time variant systems are present. We average both the switching periods to get the differential equation. The derivatives of the inductor currents and capacitor voltages are defined by applying KCL and KVL for substructure. These currents and voltages are averaged over one switching cycle.

1.1.2 Normalization with frequency:

The Runge-Kutta algorithm used in ode23 uses a variable step length. The step length is decreased for large magnitude derivatives and increased for smaller magnitude derivatives.

[5] Unfortunately, the values of physical components typically result in longer simulation

times. This issue is addressed by normalizing with respect to switching frequency. The unit of time is in seconds and unit of frequency is the inverse of seconds. A normalization results from product of frequency and time. The use of ode23 for DCM simulation presents a problem. The non constant steplength leads to inconsistent inductor current extinction times. A constant steplength rk algorithm is used in case for DCM simulation.

1.1.3 Simulation in MATLAB:

The simulation of CCM converters is simple when compared to DCM converter simulation. The switch control variable is switched between zero and one based on whether current value is within off-time or on time portion of the switching period. We use ode23 algorithm to solve the differential equation. The simulation of DCM requires rk algorithm to be run for many cycles as specified by variable T. Once the data for the first cycle is computed, the state variables are extracted into temporary variables i_L and v_C . The second loop searches for negative values of inductor current within off time interval and replaces those values with zero. The inductor current and computed capacitor voltage values are stored in I_L and V_C . The initial conditions are subsequently reset to zero inductor current and final value of capacitor voltage from present cycle. The initial time is set to the beginning of next cycle and counter is set to next cycle.

1.2 Types of DC-DC converter:

1.2.1 Buck Converter:

This converter is used to decrease the input DC voltage to lower DC voltage. The converter consists of output inductor, semiconductor switch, diode and output capacitor as seen in Fig 1.1 (Topology of buck converter)

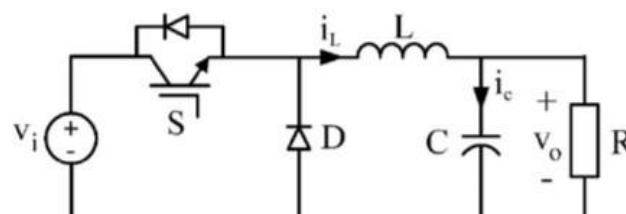


Figure 1.1: Topology of Buck Converter

1.2.2 Boost Converter:

This converter is used to increase the output DC voltage to higher than input DC voltage. The converter has same components as buck converter except for the location of components. Inductor is placed at the input of the converter. The figure 1.2 shows the circuit topology of Boost converter.

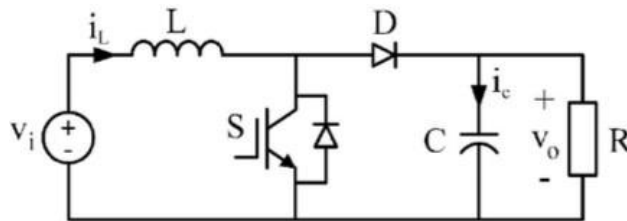


Figure 1.2: Topology of Boost Converter

1.2.3 Buck-Boost converter:

The converter has the ability to increase and decrease the input DC voltage. It combines both Buck and Boost converters and the main difference is the output voltage polarity.

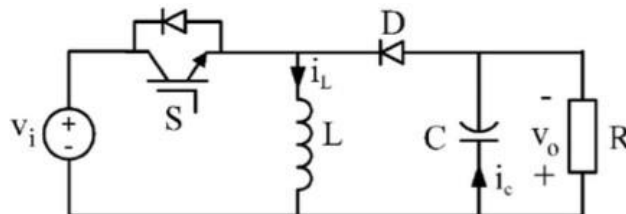


Figure 1.3: Topology of Buck-Boost Converter

1.3 Simulation of CCM and DCM

1.3.1 Continuous Conduction Mode

The initial conditions of the simulation are chosen as the load current and the desired output voltage in order for the system to reach the steady-state condition in the shortest amount of time. Although

the variable name t is used in the files, the independent variable is the normalized τ , which represents the number of cycles of the PWM switching frequency. The specified simulation interval of $[0 \ 10]$ thus presents a time interval of 10 cycles, or $10/5000 = 2$ ms. [6] The binary switching control u is based on MATLAB's sign function, which is a numerical implementation of the signum function, $G(x) = 1$ when x is greater than 0 and $G(x) = -1$ when x is lesser than 0. When $x = 0$, $G(x)$ is undefined. The sign function works similarly, except that when the argument is zero, sign returns a value of zero. As used in the function file of , sign returns a value of 1, -1, or 0 based on whether the quantity $r - \text{fix}(t) - D$ is positive, negative, or zero, respectively. Variable t represents the current value of r . The fix function truncates any fractional part of r and leaves only the integer part. The quantity $t - \text{fix}(t)$ is thus the fractional part of r . For example, if $t = 5.734$, then $\text{fix}(t) = 5$, and $t - \text{fix}(t) = 0.734$. Since t represents cycles, the quantity $t - \text{fix}(t)$ represents the fraction of a cycle. If this fraction is greater than the duty ratio, then the quantity $t - \text{fix}(t) - D$ is positive, and $u = 0.5 * (1 - 1) = 0$. This value of t corresponds to a point in the off-time interval of the switching period. The primary switch is therefore open and the inductor is disconnected from the source. If the cycle fraction is less than the duty ratio, then the quantity $t - \text{fix}(t) - D$ is negative, and the binary switch becomes $u = 0.5 * [1 - (-1)] = 1$. This value of r falls within the on-time interval of the switching period during which the inductor is connected to the source [6]

1.3.2 Discontinuous conduction mode

The cycle-by-cycle simulation requires rk4 to be repeated for as many cycles as specified by variable T in the first for statement. Once the data for one cycle is computed, the state variables are extracted into temporary variables iL and vC . The second for loop searches for negative values of inductor current within the off-time interval and replaces those values with zero. The processed inductor current and computed capacitor voltage are then stored in vectors IL and VC , respectively, while the normalized time vector t is stored in vector τ . The initial conditions are subsequently reset to zero inductor current and the final value of capacitor voltage from the present cycle. The initial time is set to the beginning time of the next cycle, and the cycle counter is advanced to the next period. [6]

Chapter 2 Literature Survey

We first reviewed models of converters. For the state space modelling we have referred various websites, videos and research papers to understand the process of calculation. We reviewed many works for state space modelling. Next, we referred some works for the simulation of converters in CCM. To understand the DC-DC converters functioning topology, we have referred to Power Electronics by Nagerath-Kothari. There are various methods for obtaining linear time invariant model of dc-dc converter circuit averaging (Wester and Middlebrook (1973) and Vorperian (1990)), and the current-injected approach (Clique and Fossard (1977) and Kislovski, Redl and Sokal (1991)) are some of them. We have chosen State-space averaging (Middlebrook and Cuk (1976) and Mitchell (1988)) as it is in matrix form and helps in easy simulation. We referred to Power electronics by M.Rashid for understanding state space averaging method and formulation of time invariant system. We have many methods for simulation of DC-DC converters. Kaoutar Bendaoud and Salah-ddine Krit and many other research papers use mathematical model building by using simulink models. Simulink is widely used in simulation of dc-dc converters and to find the values of inductance, capacitance and resistor. We calculated the capacitance and inductance values from CCM equations by studying various models available online.

Chapter 3 Work Done

We were successfully able to simulate CCM and DCM process for DC-DC converters and have derived the differential equations by the process of State space modelling. Then, we have derived state space models for buck, boost and buck-boost and normalized it with frequency for Matlab. We wrote a program in Matlab to solve the differential equations and observe the output values. We assigned the values of various components in circuit with help from various models reviewed by us. Finally we observed the outputs and tried to interpret data for better capacitance and inductance values.

3.1 State space modelling:

The figure 1 shows the topology of Buck converter by combining the equation of both ON state and OFF state and by normalizing with respect to frequency, we get the state space as shown in figure 3.1

$$\frac{d}{d\tau} \begin{bmatrix} i \\ v \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_f} \\ \frac{1}{C_f} & -\frac{1}{RC_f} \end{bmatrix} \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} \frac{V_s}{L_f} \\ 0 \end{bmatrix} u.$$

Figure 3.1: Normalised state space model for Buck

Similarly Fig 3.2 and Fig 3.3 show the state space model of boost and buck-boost converter

$$\frac{d}{d\tau} \begin{bmatrix} i \\ v \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_f} \\ \frac{1}{C_f} & -\frac{1}{RC_f} \end{bmatrix} \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} \frac{v}{L_f} & \frac{1}{L_f} \\ -\frac{i}{C_f} & 0 \end{bmatrix} \begin{bmatrix} u \\ V_s \end{bmatrix}.$$

Figure 3.2: Normalised State Space model for Boost

$$\frac{d}{d\tau} \begin{bmatrix} i \\ v \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_f} \\ \frac{1}{C_f} & -\frac{1}{RC_f} \end{bmatrix} \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} \frac{1}{L_f}(v+V_s) \\ -\frac{i}{C_f} \end{bmatrix} u.$$

Figure 3.3: Normalised State Space Model for Buck-Boost

3.2 Simulation in MATLAB:

Matlab is a very good platform for the simulation process as it has inbuilt functions to solve differential equations and also the matrix structure upon which it is based. Two m-files are required for the simulation of State-Space model. The first file contains the circuit parameters along with definition of state transition and control input matrices. The second file contains the control function and state derivative function. The results of the simulation are shown below

3.2.1 CCM Simulation Of Converters

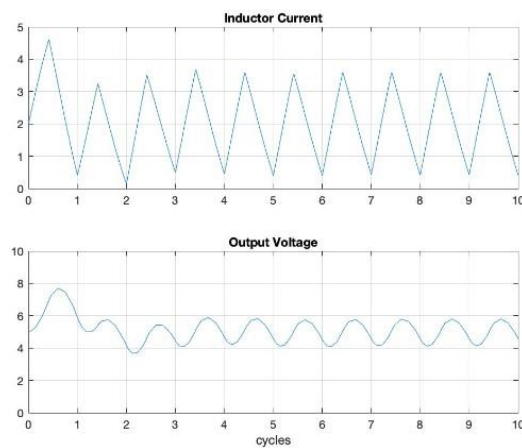


Figure 3.4: CCM of Buck

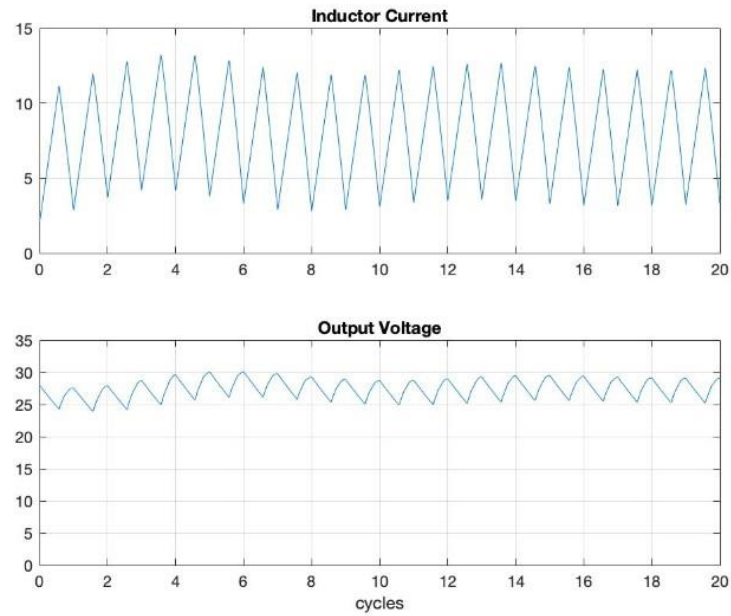


Figure 3.5: CCM of Boost

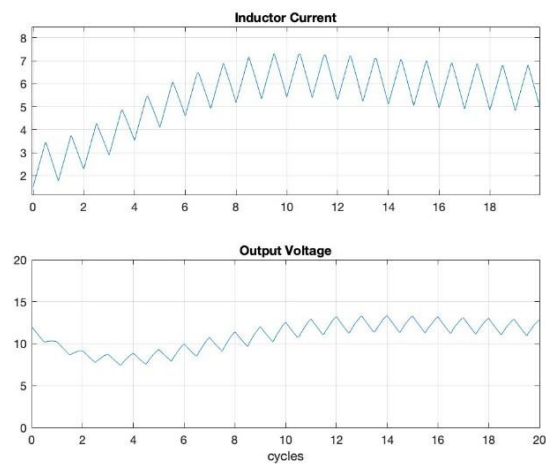


Figure 3.6: CCM of Buck-Boost

3.2.2 DCM Simulation of Converters

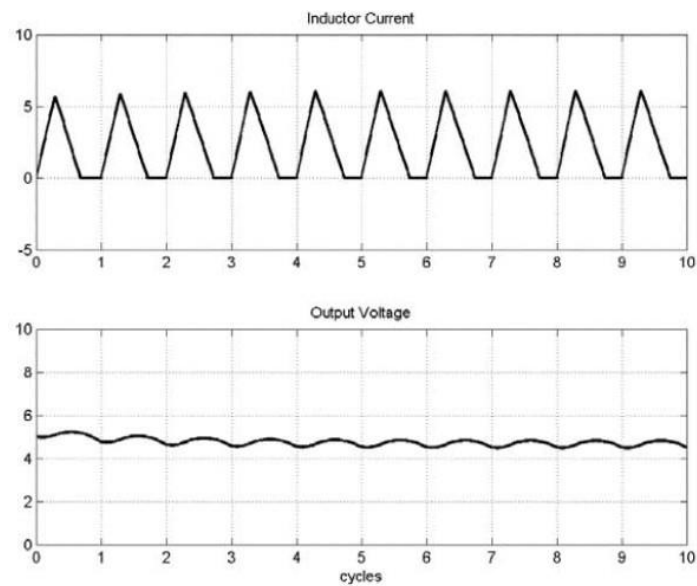


Figure 3.7: DCM of Buck

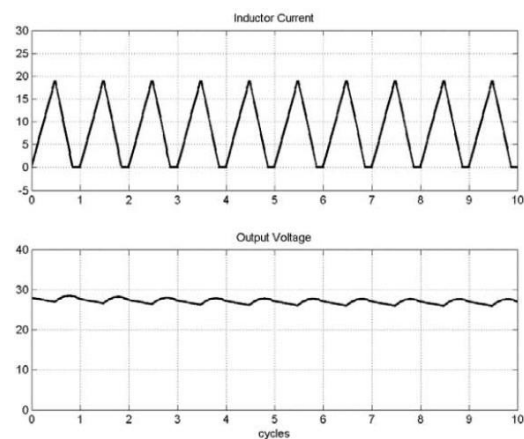


Figure 3.8: DCM of Boost

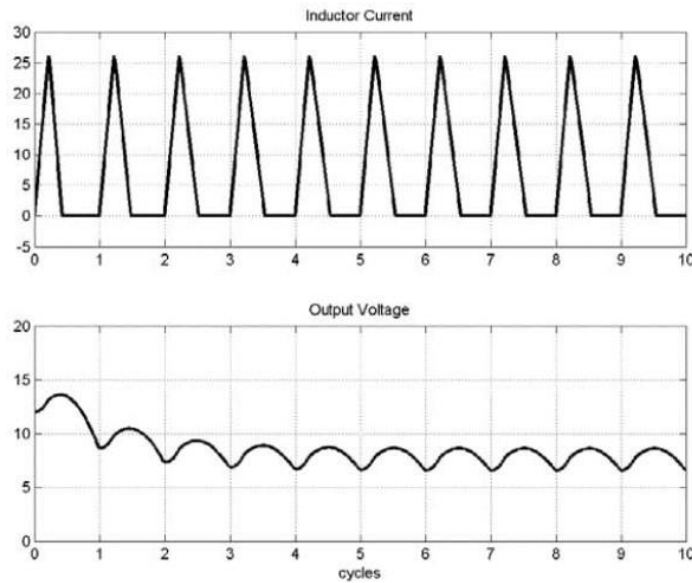


Figure 3.9: DCM of Buck-Boost

Chapter 4 Experimental Evaluation

We performed CCM operation on Buck converter. The buck converter used in the setup has the following parameters

$R=250$ ohms $L=2.1$

MilliHenry $C=120$ MicroF

Switching frequency =66kHz Voltage across

load(Capacitor)=15V

The results of the simulation and from the lab matched. We observed the output voltage and voltage across inductor and used it to calculate Inductor current, which was also verified.

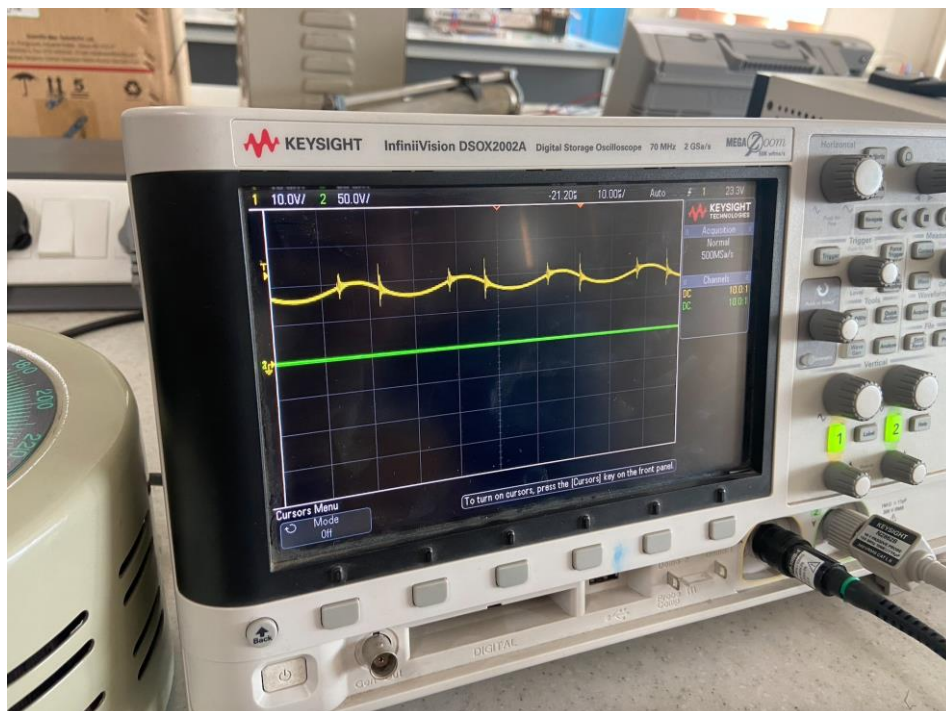


Figure 4.1: DCM of Buck-Boost

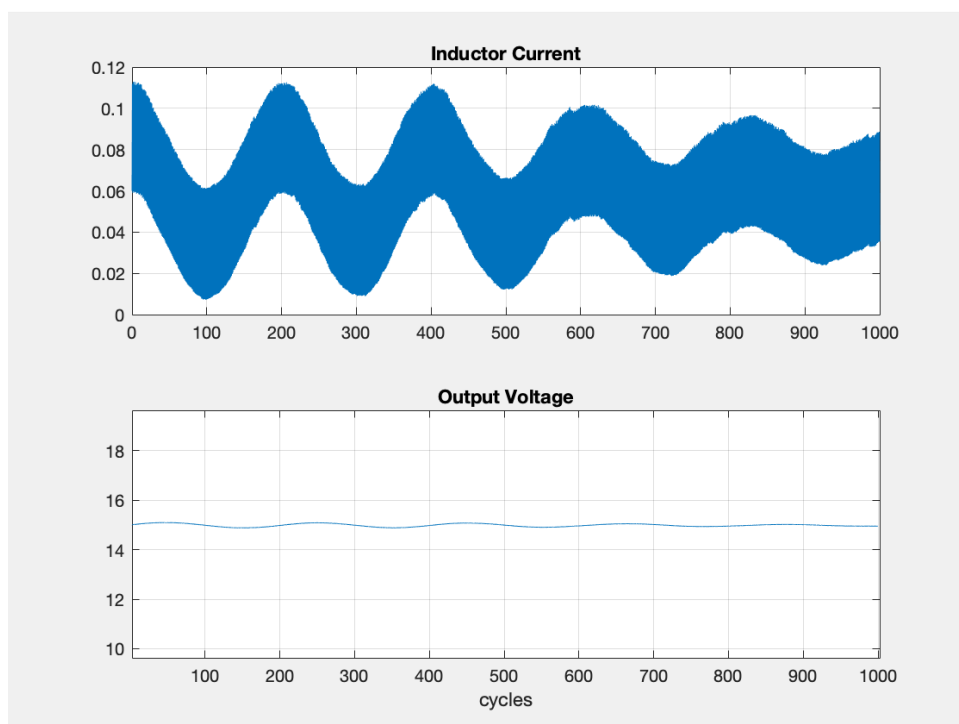


Figure 4.2: DCM of Buck-Boost

Chapter 5 Conclusion

The DC-DC converters are widely used in many industrial applications. As renewable energy sources became more popular, the use of converters have gotten more important. Therefore, three-types of DC-DC converters, such as boost, buck and buck-boost converter, are investigated in this study. The MATLAB software simulates circuits successfully. However, simulations may take a long time especially if the circuit is complex and have more switching devices. Therefore, mathematical model/State space model of converter is used to shorten the simulation time and to analyze the system for many parameters fast. In the study, the models and simulation circuit of three converters presented in detail. The model can be used in code for many parameter analyses fast. The converters are simulated in both CCM and DCM modes, The simulation results reveal the dynamic behavior of CCM converters and confirm the theory. The inductor current wave form has the level-shifted triangular waveform typical of CCM converters. The simulation results of the buck converter reveal a common problem with some DC-DC converters i.e; significant voltage overshoot at start-up. This overshoot could damage the equipment supplied by the converter. In such over-voltage transients, voltage suppression techniques are employed to absorb the potentially harmful energy. MATLAB proves to be an excellent platform for the simulation of DC-DC converters. Unlike other softwares, no circuit schematic or cryptic netlist is required for the simulation. Only the circuit equations derived by application of KCL and KVL and formed into a normalized state-space model. The simulation methods for both CCM and DCM operations presented are applicable to virtually any DC-DC converter.

Chapter 6 Future Prospects

To obtain State Space Modelling of other DC-DC converters such as cuck, flyback converter.

To obtain high performance control of a dc-dc converter, a good model of the converter is needed. The load usually affects the dynamics and one way to take this into consideration is to regard the load as a part of the converter. The load is often the most variable part of this system. If the load current and the output voltage are measured there are good possibilities to obtain a good model of the load on-line. Adaptive control can then be applied to improve the control.

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