

Modelling of Buck DC-DC Converter Using Simulink

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ABSTRACT: In this paper, a mathematical model of a Buck Converter for simulation using Simulink without any Sim Power System Elements is illustrated. We also explain how to use Matlab's Tuning tools to obtain better rise time, settling time and peak overshoot.

KEYWORDS: Buck converter, Transfer function, PID controller, Pulse Width Modulation (PWM), Duty Cycle, Matlab, Simulink.

I. INTRODUCTION

Switched mode DC-DC converters are some of the simplest power electronic circuits which convert one level of electrical voltage into another level by switching action. These converters have received an increasing deal of interest in many areas. This is due to their wide applications like power supplies for personal computers, office equipment, appliance control, telecommunication equipment, DC motor drives, automotive, aircraft, etc. The analysis, design, control and stabilization of switching converters are the main factors that need to be considered [1]. Many control methods are used for control of switch mode DC-DC converters and the simple and low cost controller structure is always in demand for most industrial and high performance applications [2]. Each control method has its own advantages and drawbacks, and its effectiveness is determined by the application where it's applied.

Whether it is for designing your own product or just experimenting with various algorithms and designs, simulation runs are mandatory before the actual physical implementation. Various tools are available for constructing and simulating electrical and electronic circuits, including Math Works SimPowerSystems. However, some might not have access to these Tools and Suites. It is possible to circumvent this by representing the system in the form of a mathematical model. Therefore, in this paper we illustrate how to model a Buck Converter using the most rudimentary blocks of Simulink, while still providing the same degree of accuracy as other tools. This paper explains the working of the model and each of its subsystems.

In section III, a brief overview of the operation of a typical DC-DC Buck Converter is provided. Section IV proceeds to explain the Simulink model of the Buck Converter and its various subsystems. In Section V, details of a simulation run and its results are discussed. In Section VI, we give our closing comments.

II RELATED WORK

Several control strategies and mathematical models have been developed by researchers. Tobias Geyer, Georgios Papafotiou, and Roberto Frasca have proposed a modeling and control approach for fixed frequency switch-mode DC-DC converters by formulating a constrained optimal control problem using hybrid systems methodologies [2]. Ned Mohan, W.P. Robbins, T.M. Undeland, R. Nilssen and Olive Mo were among the first to present means of simulating Power Electronics and Motion Control systems [6]. Great strides have been made to incorporate soft computing techniques such as Fuzzy Logic, Genetic Algorithm etc, into the control strategies as well. There are also numerous publications on tuning methods of a PID controller for a Buck Converter.

III. PRINCIPLE OF OPERATION OF A BUCK CONVERTER

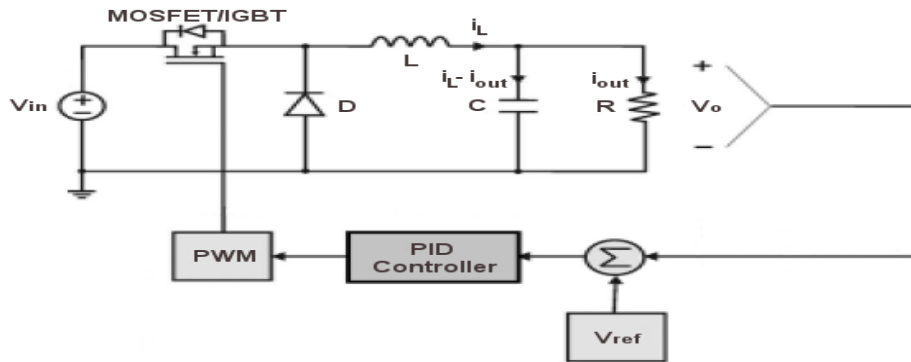


Figure 1: Voltage step down chopper with feed back controller

Figure 1 shows the circuit configuration of the voltage step down chopper which converts unregulated DC to regulated DC. The chopper is operated by turning the MOSFET ON and OFF at a high switching frequency. Figure 2 shows the output voltage and current waveforms of the chopper.

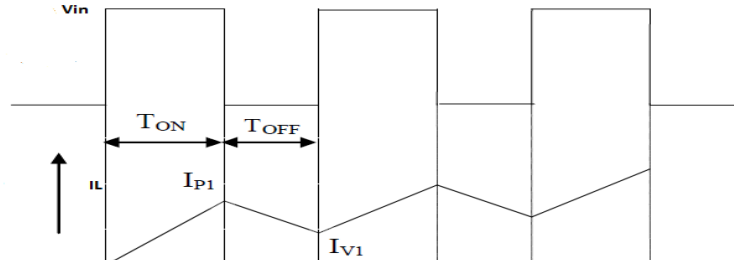


Figure 2: Output voltage and current waveform

When the MOSFET is turned ON, the voltage V_{in} is applied in reverse across the power diode. Therefore diode must stay OFF as long as MOSFET remains ON. The ON state of MOSFET always implies the OFF state of diode. With the MOSFET turned ON, current I_L begins to build up. The growth of I_L occurs exponentially due to the inductance L . The MOSFET is kept ON for a time interval T_{ON} , and OFF for the interval T_{OFF} . At the instant when MOSFET is turned OFF, I_L has a finite value (I_{P1}), which is the peak value of the output current during the first chopper cycle. This peak current occurs at the instant the MOSFET turns OFF. The presence of the inductance L prevents the sudden drop of I_L to zero. The decay of I_L causes an induced voltage $L \frac{di_L}{dt}$ to appear across the inductance. Because of this voltage, the diode becomes forward-biased and causes the current flow to continue and decay exponentially. The term “Free-Wheeling” is commonly used to describe the flow of current in this manner without the aid of a voltage source, but solely due to the stored energy in the inductance. The purpose of the diode is to provide the free-wheeling path for the MOSFET when it is turned OFF. Therefore, the diode automatically turns ON at the instant the MOSFET switches off due to the presence of an inductance with stored energy. The decay of I_L continues as long as MOSFET remains OFF, that is, for a duration T_{OFF} . The lowest value to which the current falls at the end of the first chopper cycle is labelled as the valley magnitude I_{V1} in Figure 2. The second chopper switching cycle commences when MOSFET is turned ON again at the end of the first T_{OFF} , and the current again starts to build up. Due to the initial current I_{V1} , the second peak I_{P2} will be larger than I_{P1} . Consequently, the valley magnitude I_{V2} at the end of the second cycle will also be larger than I_{V1} . In this way, as the switching progresses, both the peak and valley magnitudes progressively increase. After several cycles, the difference between successive cycles becomes negligibly small. We say that the circuit conditions have reached steady state [3,4]. This means that the peak current is effectively the same

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in successive cycles. A similar statement is true for the valley current. The relation between the input voltage (V_{in}), output voltage (V_{out}) and duty cycle (D) is given by:

$$V_{out} = V_{in} \times D \text{----- (1)}$$

Where

$$D = \frac{T_{on}}{T_{on} + T_{off}} \text{----- (2)}$$

The switching duty cycle can be varied ideally in the range 0-1 by variation of the ON time, thus the output voltage is always less than or equal to input voltage and hence the name step down or buck chopper.

Output voltage ripple of the DC-DC converter is minimized by proper selection of inductor and capacitor, which is given by

$$L = \frac{D[V_{in} - V_{out}]}{I_{ripple} \times F_s} \text{----- (3)}$$

$$C = \frac{I_{ripple}}{8 \times F_s \times \Delta V} \text{----- (4)}$$

Where V_{in} = Input Voltage of the Buck Converter,
 V_{out} = Output voltage,
 D = Duty Cycle,
 F_s = Switching Frequency

I_{ripple} is the inductor ripple current, it is usually 30% of maximum output current. ΔV is the output voltage ripple, it is usually 1% of output voltage. ESR is the effective series resistance of the capacitor, and is detailed from manufacturer's catalog (usually 0.03Ω). A capacitor with low ESR will help to minimize the ripple on the output voltage.

Continuous and Discontinuous Current Modes

If the value of the inductance is reduced to the critical point, the valley current will decay and finally become zero at the end of the duty cycle. A further decrease in L will cause the current to fall to zero even before the completion of the OFF period of the chopper. The current builds up from an initial zero value during T_{ON} in the next chopper cycle. This operation of the chopper is called discontinuous load current mode. If the current is nonzero for all the chopper period, the chopper is said to be operating in continuous load current mode. This is achieved by appropriate selection of chopper switching frequency or inductance value, or both.

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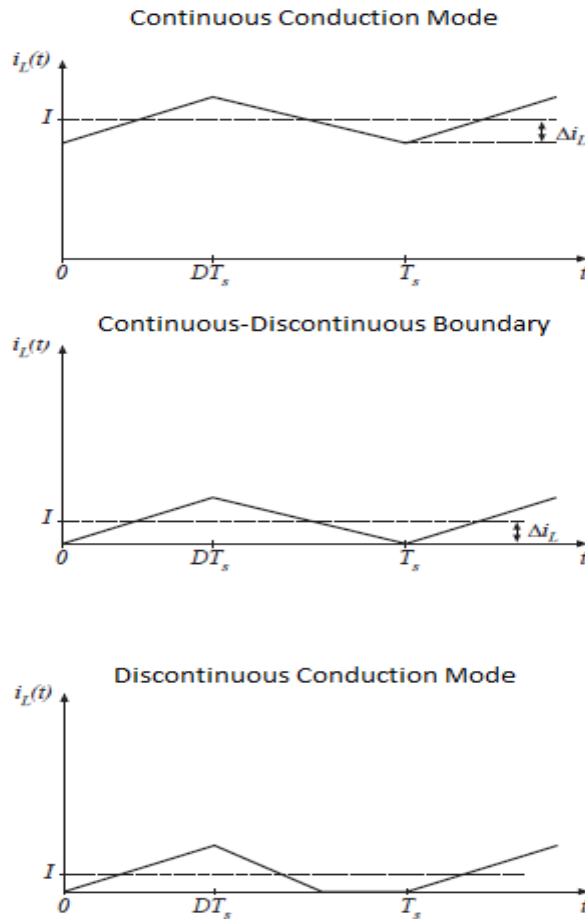


Figure 3: Continuous and Discontinuous Operating Modes

IV. MODELLING IN SIMULINK

The Simulink Model for the Buck Converter is shown in figure 4. The model consists of three constant blocks that are set by the user, namely: Input Voltage (V_{in}), Reference Output Voltage (V_{ref}) and Load Resistance (R_o).

In addition to the Main Input parameters, the model consists of two more subsystems, namely:-

- PWM Generator: This subsystem accepts duty cycle in decimal form from the controller and outputs the required PWM waveforms of the corresponding duty cycle.
- Buck Converter: This subsystem includes all the blocks to model the Buck converter in mathematical form and produces the Output Voltage and Current waveforms based on its inputs.

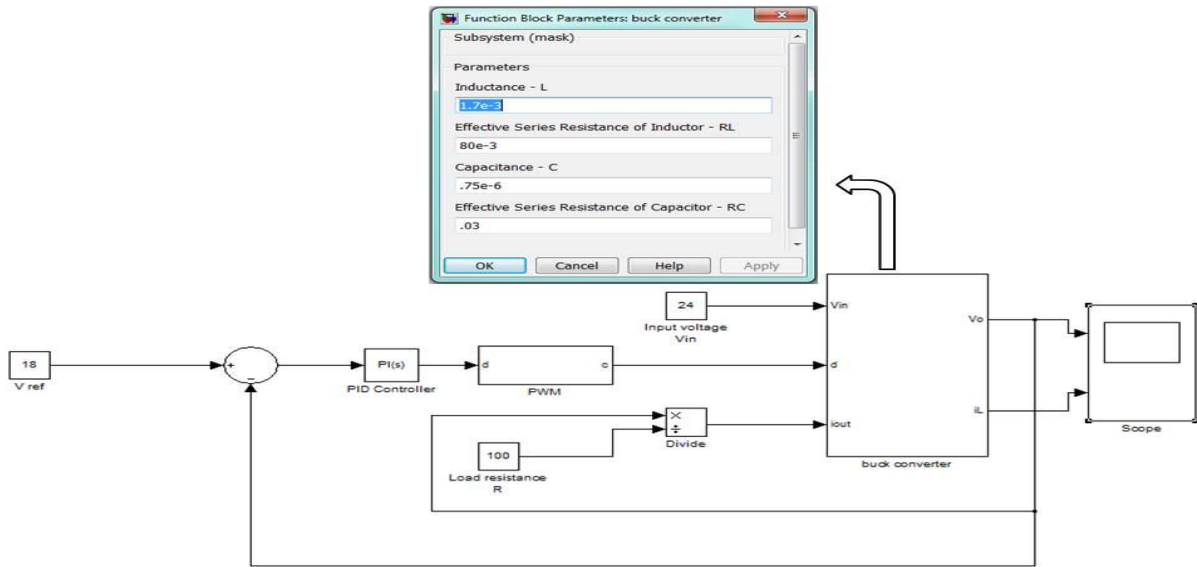


Figure 4: Main Simulink Model

A. PWM Waveform Generator Subsystem

This block is responsible for producing PWM pulses of varying duty cycle. As already explained, the circuit has two operating conditions, the Duty Interval (T_{on}) when the Chopper Switch is ON and the Free Wheeling mode (T_{off}) when the switch is OFF. To simulate both these conditions in the same model, switch blocks can be employed. However, the PWM pulses are easier to implement and also more convenient for our mathematical model, especially in the case of a closed loop system with a controller. The two inputs to the Subsystem are:

- The duty cycle from the controller in decimal form.
- Switching Frequency F_s , as a parameter in the mask as shown in figure 5.

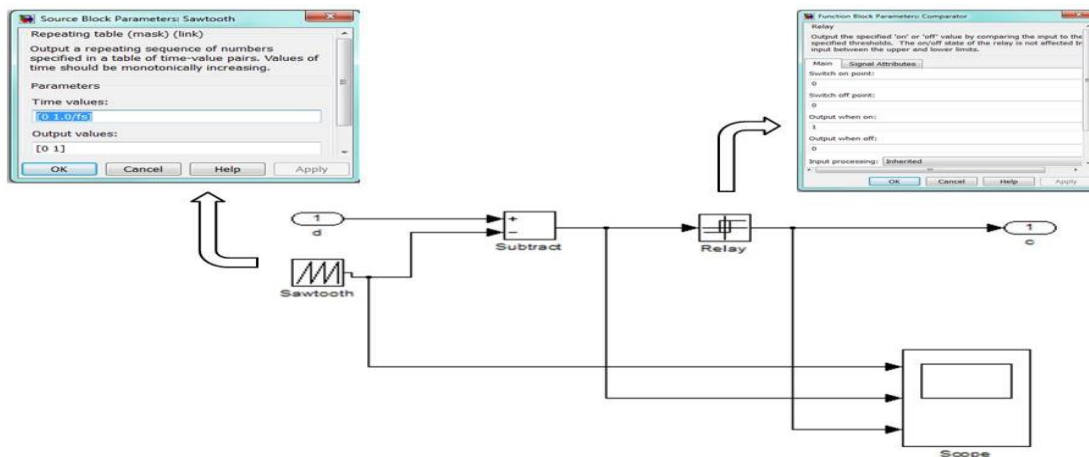


Figure 5: PWM Subsystem

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Figure 6 shows the output waveforms of the subsystem for a constant 0.6 duty cycle. A Repeating Sequence Block (Waveform 1 in Figure 6) is inserted and configured to output a saw-tooth waveform of time values (0 1/fs) and Output Values (0 1). The magnitude of this waveform is subtracted from the duty cycle (decimal value) to yield a mirrored version of the saw tooth waveform whose amplitude ranges from D to D-1. This waveform (Waveform 2 in Figure 6) possesses a positive value whenever the required PWM signal is high and a negative value where the PWM pulse is low. This fact is exploited to generate the PWM pulses by using a Relay block that is configured to switch on (Output=1) and off (Output=0) during the zero crossings. The resulting waveform (Waveform 3 in Figure 6) is a PWM Signal of the required duty cycle.

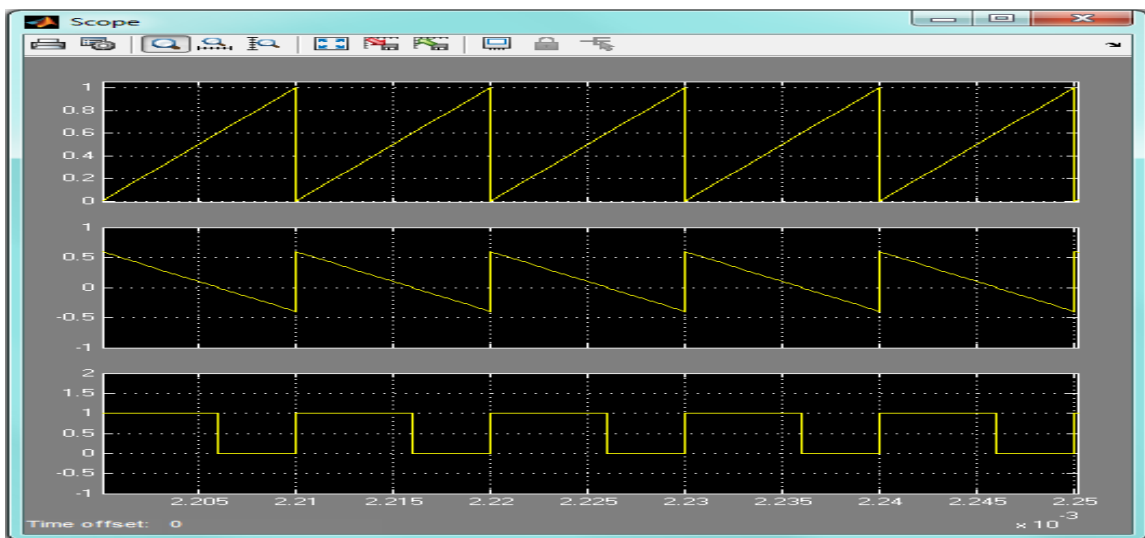


Figure 6: PWM waveforms

B. Buck Converter Subsystem

This subsystem carries out almost all the computations to produce the Output Voltage and Load Current Waveforms. The inputs to the subsystem are the Input Voltage, Duty cycle and Load Current. In addition, the following values need to be declared as masked parameters: Inductance (L), Inductance Series Resistance (R_L), Capacitance (C), and Capacitance Series Resistance (R_C). Underneath the mask is the actual implementation as shown in figure 7:

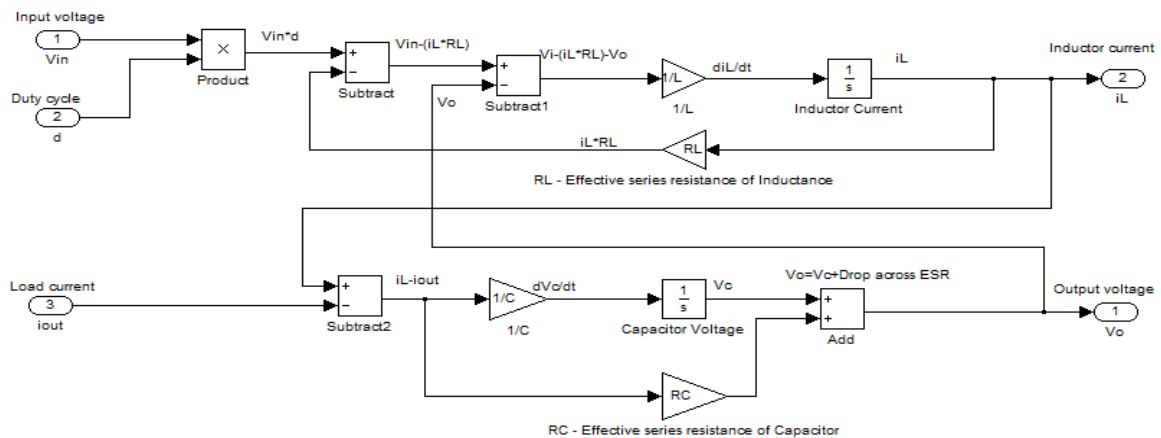


Figure 7: Buck Converter Subsystem

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The subsystem consists of two main loops, which are essentially differential equations which provide the Inductor Current and Output Voltage.

As stated in the principle of operations, the Buck Converter circuit has two modes of operation:

1. The Duty Interval during which the chopper switch is closed and the input voltage source is applied across the Load.
2. The Free Wheeling Interval during which the switch is open and the input voltage source is cut off from the Load.

To implement this in model form, we multiply the Input Voltage V_{in} with the PWM waveform. The result is that the Input Voltage is included in the KVL Equation when the PWM waveform is high ($V_{in} \times 1 = V_{in}$) and omitted when it is low ($V_{in} \times 0 = 0$).

The first loop is responsible for computing the Inductor current by solving the differential equation obtained from applying KVL to Figure 1.

$$V_{in} D = L \frac{di_L}{dt} + i_L R_L + V_o \text{-----} (5)$$

$$L \frac{di_L}{dt} = V_{in} D - i_L R_L - V_o \text{-----} (6)$$

$$i_L = \frac{1}{L} \int (V_{in} D - i_L R_L - V_o) dt \text{-----} (7)$$

Where V_{in} = Input Voltage of the Buck Converter.
 $D=1$ when Duty Cycle is ON and $D=0$ when Duty Cycle is OFF.
 i_L =Inductor Current
 R_L =Effective Series Resistance of Inductance
 V_o =Output Voltage of the Buck Converter
 L =Inductance Value in Henry

The second loop calculates the Output Voltage which is the sum of the Capacitor Voltage and the drop across the Capacitor Series Resistance (R_c). Applying KCL at the capacitor node we get:

$$C \frac{dV_c}{dt} = i_L - i_{out} \text{-----} (8)$$

$$V_c = \frac{1}{C} \int (i_L - i_{out}) dt \text{-----} (9)$$

$$V_o = V_c + \text{Drop across ESR of Capacitor}$$

$$V_o = V_c + R_c (i_L - i_{out}) \text{-----} (10)$$

Where i_{out} =Load Current,
 C =Capacitance in Farad,
 V_c =Voltage across Capacitor,
 R_c =Effective Series resistance of the Capacitor.

The Inductor Currents and Output Voltage are the outputs of the subsystem. As shown in Figure 4, the Output Voltage is divided by the Load Resistance to obtain the Load Current, which is fed back to the subsystem.

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C. PID Controller

The default PID controller Simulink block is utilized to generate the required duty cycle in decimal form (eg 45% duty cycle =0.45) based on the error signal. The P, I, and D parameters can be entered manually or can be tuned to some extent using the tools provided by Matlab, which also provides the Bode Plots for further analysis. However, an attempt to run the tuning tools will result in a linearization error as the forward path of the control loop linearizes to zero at certain points due to PWM logic. To circumvent this, the Buck Converter needs to be modelled as a Transfer Function to permit automatic tuning.

By applying Laplace Transform to Eqn (5), we get:

$$V_{in}D = Li_Ls + i_LR_L + V_o \text{-----(11)}$$

Let us assume $V_c=V_o$ by neglecting the drop across R_c . Using Laplace Transform on Eqn (8) and rearranging the terms, we get

$$i_L = \frac{V_o}{R} + CV_0s \text{-----(12)}$$

By substituting the value of i_L in Equation (11) and rearranging the terms, we obtain the open loop transfer function of the Buck Converter:

$$\frac{V_o}{D} = \frac{\frac{V_{in}}{LC}}{s^2 + s\left(\frac{1}{R_oC} + \frac{R_L}{L}\right) + \left(\frac{1}{LC} + \frac{R_L}{R_oLC}\right)}$$

Where V_o =Output Voltage, V_{in} =Input Voltage, R_o =Load Resistance in Ohm (Ω), L =Inductance in Henry (H), C =Capacitance in Farad (C), R_L =Effective Series Resistance of Inductance in Ohm (Ω). The transfer function model of the Buck Converter is shown in figure 8:

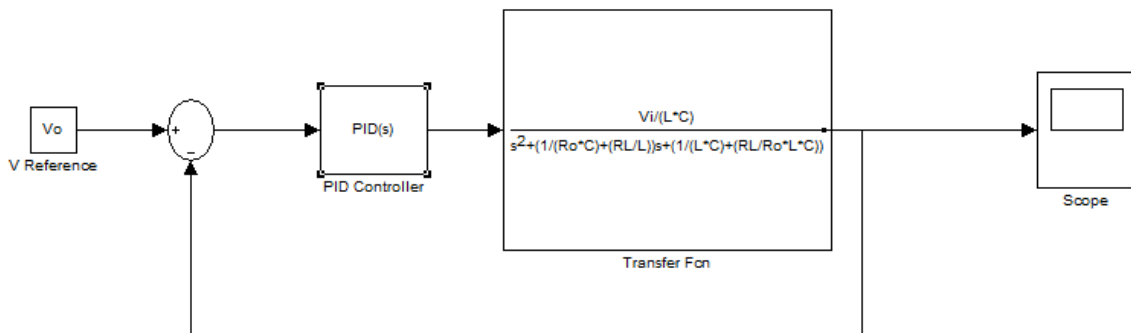


Figure 8: Transfer Function Model

The tuned P, I and D parameters can then be substituted in the main model. Since the data can be exported to the workspace, one is free to implement their own control algorithms with the Fuzzy Logic, Neural Network toolboxes in Matlab or other computing techniques.

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V. VERIFICATION

A simulation run for a Buck Converter is carried out whose design parameters are specified in Table 1.

Table 1: Design Parameters

| Parameters | Values |
|------------------------------------|--------|
| V _{in} | 24 V |
| V _{out} | 18 V |
| Load Resistance | 100Ω |
| F _s | 50KHz |
| L | 1.7 mH |
| C | 0.75μF |
| ESR Of Inductor (R _L) | 0.08 Ω |
| ESR Of Capacitor (R _c) | 0.03 Ω |

The P, I and D values are obtained by using the Tuning tools provided by Matlab in the Transfer Function model as shown in Figure 8, and then substituted in the main model.

Table 2: Transient Response Values

| Parameters | Values |
|---------------|----------|
| Rise Time | 0.719 ms |
| Settling Time | 1.32ms |
| % Ripple | 0.56% |
| Peak Time | 1ms |

To simulate a change in operating condition which is likely to happen in practical implementation, the Input voltage is stepped up to 25 V in the form of a pulse between time instants 0.003 to 0.006 to see if the controller maintains the required output voltage of 18V. The response is obtained as shown in Figure 9.

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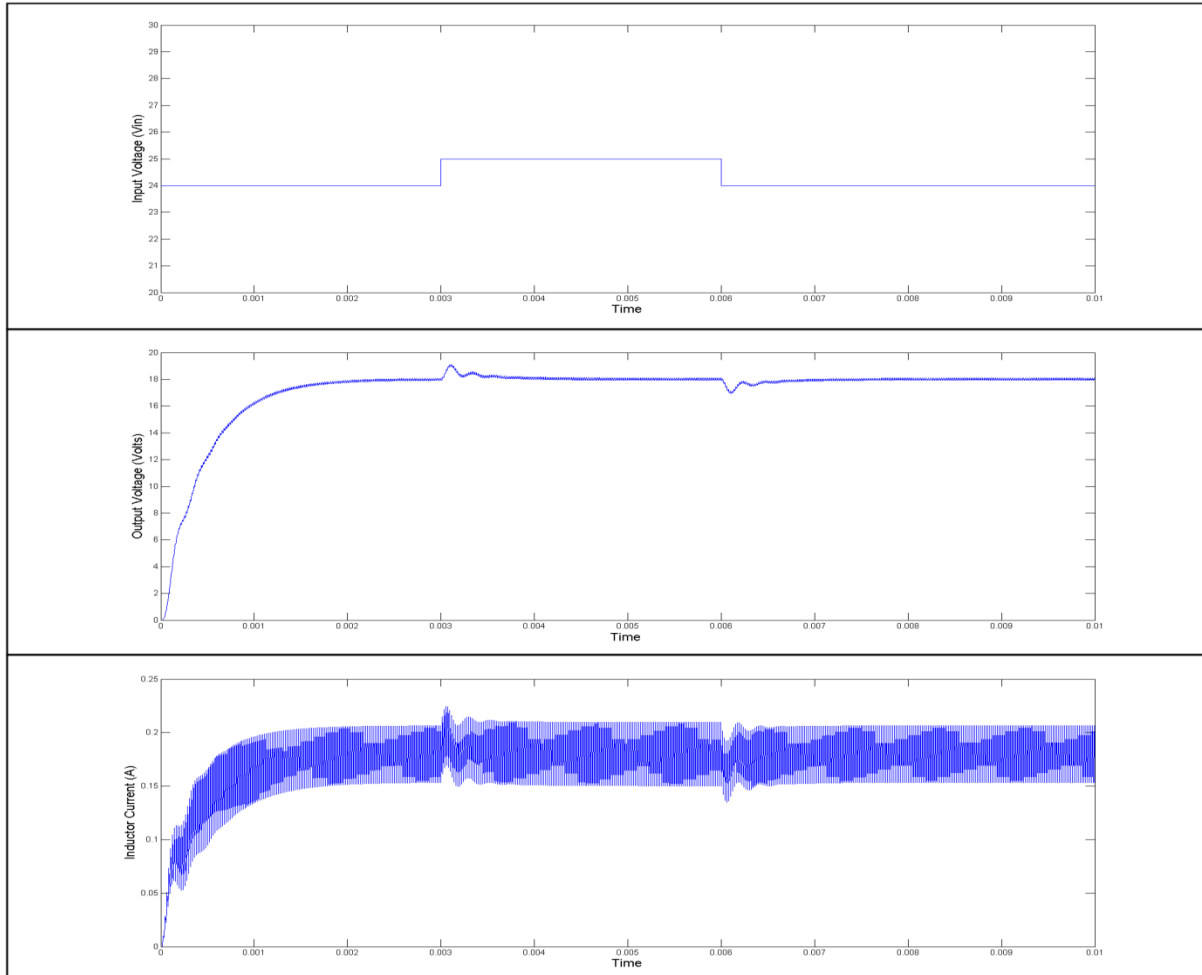


Figure 9: Input Voltage, Output Voltage and Inductor Current waveforms

The Output voltage rises to 18.8 V when the input voltage rises to 25 V and then reverts to 18V within 0.4 ms. Similarly, when the input voltage reverts to normal, a small ripple is experienced in the output voltage and current before it settles back to its steady state. The waveforms obtained from this model are nearly identical to a Buck Converter modelled using SimPowerSystems with only some minor deviation appearing in the Inductor Current.

VI. CONCLUSION

In this paper, we have provided a brief overview of the operation of a Buck DC-DC converter, and proceeded to illustrate an alternate way to model the converter using only Simulink blocks, without the need of any SimPowerSystems. The mathematical model is derived from the system equations and provides an accurate representation of the Buck Converter. The Transfer Function of the system is also discussed in order to permit the use of the controller tuning tools provided by Matlab. One is free to replace the default PID block with their own algorithms.

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