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A Low Voltage Dynamic Synchronous DC-DC Buck Converter

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Abstract: This paper presents the design and modeling of synchronous DC-DC buck converter for device applications low consumption using Matlab/Simulink. In this work, the steady-state and average-value models for buck converter are analysed and it offers the modeled equations and simulation techniques of standard buck converter topology including variable loads. The goals of the designer are stabilized output voltage from a given input DC voltage using a Proportional Integral Derivative (PID) controller.

Keywords: Proportional Integral Derivative, DC-DC, Buck Converter, Matlab/Simulink, Controlled Converter

1. Introduction

Current trends in consumer electronics demand progressively lower supply voltages due to the unprecedented growth and use of wireless appliances. Portable devices, such as laptop computers and personal communication devices require ultra-low power circuitry to enable longer battery operation. The key to reducing power consumption while maintaining computational throughput and quality of service is to use such systems at the lowest possible supply voltage. DC-DC buck converters [1-4] play an important role in modern Very-Large-Scale Integration (VLSI) system. Controller design for any system needs knowledge about system behavior [5-9]. Usually this involves a mathematical description of the relation among inputs to the process, state variables, and output. This description in the form of mathematical equations which describe behavior of the system (process) is called model of the system. This paper describes an efficient method to learn, analyze and simulation of power electronic converters, using system level nonlinear, and switched state- space models. The MATLAB/SIMULINK software package can be advantageously used to simulate power converters [10-13]. Figure 1 shows the basic topology of Synchronous DC-DC buck converter.

The paper is organized as follows. The synchronous buck converter is discussed and its key waveforms are presented in Section 2. In Section 3, the analysis and development of the mathematical equations of the buck converter and their modeling under MATLAB/SIMULINK are presented. In Section 4, results of the converter and discussions are offered. Finally, the paper is concluded in Section 5.
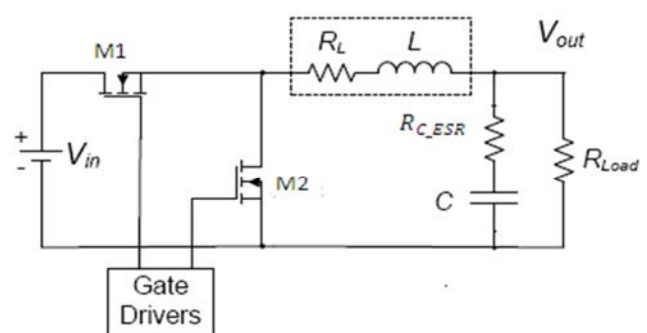

Figure 1. Basic buck converter circuit.

2. Buck Steady-State Continuous Conductions Mode Analysis

The following is a description of steady-state operation in continuous conduction mode [14]. The main result of this section is a derivation of the voltage conversion relationship for the continuous conduction mode buck power stage. This

result is important because it shows how the output voltage depends on duty cycle and input voltage or, conversely, how the duty cycle can be calculated based on input voltage and output voltage. Steady-state implies that the input voltage, output voltage, output load current, and duty-cycle are fixed and not varying. Capital letters are generally given to variable names to indicate a steady-state quantity.

In continuous conduction mode, the buck power stage assumes two states per switching cycle [15, 16]. The ON state is when transistor MOS (M1) is ON and transistor MOS (M2) is OFF. The OFF state is when transistor MOS (M1) is OFF and transistor MOS (M2) is ON. A simple linear circuit can represent each of the two states where the switches in the circuit are replaced by their equivalent circuits during each state. The circuit diagram for each of the two states is shown in figure 2.
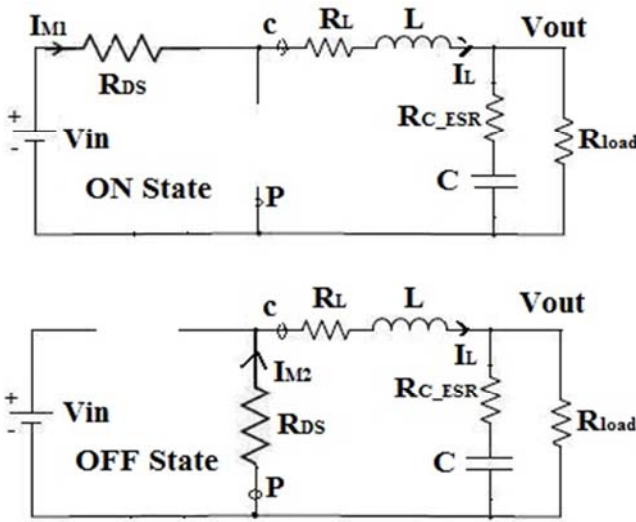

Figure 2. *Buck power stage states.*

The duration of the ON state is $D \times T_S = T_{ON}$ where D is the duty cycle, set by the control circuit, expressed as a ratio of the switch ON time to the time of one complete switching cycle T_S. The duration of the OFF state is called T_{OFF}. Since there are only two states per switching cycle for continuous mode, T_{OFF} is equal to $(1 - D) \times T_S$. These times are shown along with the waveforms in figure 3.

Referring to figure 2, during the ON state, M1 presents a low resistance $R_{DS}(ON)$, from its drain to source and has a small voltage drop of $V_{DS1} = I_L \times R_{DS}(ON)$. There is also a small voltage drop across the dc resistance of the inductor equal to $I_L \times R_L$. Thus, the input voltage V_{in} minus losses $(V_{DS1} + I_L \times R_L)$ is applied to the left-hand side of inductor L, M2 is OFF during this time. The voltage applied to the right hand side of L is simply the output voltage V_{out}, the inductor current I_L flows from the input source V_{in} through M1 and to the output capacitor and load resistor combination.

During the ON state, the voltage applied across the inductor is constant and equal to

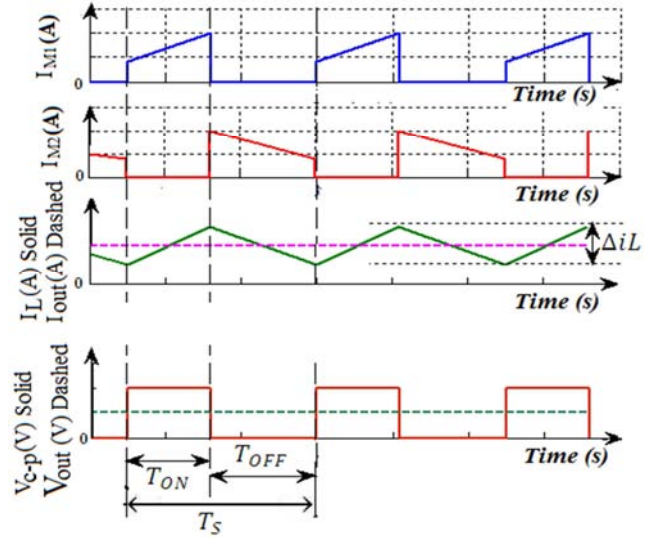$$V_L = V_{in} - V_{DS1} - I_L \times R_L - V_{out}$$

Figure 3. *Continuous-mode buck power stage waveforms.*

Adopting the polarity convention for the current I_L shown in figure 2, the inductor current increases as a result of the applied voltage. Also since the applied voltage is essentially constant, the inductor current increases linearly. This increase in inductor current during T_{ON} is illustrated in figure 3. The amount that the inductor current increases can be calculated by using a version of the familiar relationship:

$$V_L = L \times \frac{di_L}{dt} \rightarrow \Delta I_L = \frac{V_L}{L} \times \Delta T$$

The inductor current increase during the ON state is given by:

$$\Delta I_L(+) = \frac{(V_{in} - V_{DS1} - I_L \times R_L) - V_{out}}{L} \times T_{ON} \qquad (1)$$

This quantity $\Delta I_L(+)$ is referred to as the inductor ripple current.

Referring to figure 2 when M1 is OFF and M2 is ON, the voltage on the left-hand side of L becomes $-(V_{DS2} + I_L \times R_L)$ with $V_{DS2} = R_{DS} \times I_L$. The voltage applied to the right hand side of L is still the output voltage V_{out}. The inductor current I_L now flows from ground through M2 and to the output capacitor and load resistor combination.

During the OFF state, the magnitude of the voltage applied across the inductor is constant and equal to $(V_{out} + V_{DS2} + I_L \times R_L)$. Maintaining our same polarity convention, this applied voltage is negative (or opposite in polarity from the applied voltage during the ON time). Hence, the inductor current decreases during the OFF time. Also, since the applied voltage is essentially constant, the inductor current decreases linearly. This decrease in inductor current during T_{OFF} is illustrated in figure 3.

The inductor current decrease during the OFF state is given by:

$$\Delta I_L(-) = \frac{V_{out} + (V_{DS2} + I_L \times R_L)}{L} \times T_{OFF} \qquad (2)$$

This quantity $\Delta I_L(-)$ is also referred to as the inductor ripple current. In steady state conditions, the current increase,

$\Delta I_L(+)$, during the ON time and the current decrease during the OFF time, $\Delta I_L(-)$, must be equal. Otherwise, the inductor current would have a net increase or decrease from cycle to cycle which would not be a steady state condition. Therefore,

$$V_{out} = (V_{in} - V_{DS1}) \times \frac{T_{ON}}{T_{ON}+T_{OFF}} - V_{DS2} \times \frac{T_{OFF}}{T_{ON}+T_{OFF}} - I_L \times R_L \qquad (3)$$

In addition, substituting T_S for $T_{ON} + T_{OFF}$, and using $D = \frac{T_{ON}}{T_S}$ and $(1-D) = \frac{T_{OFF}}{T_S}$, the steady-state equation for V_{out} is

$$V_{out} = (V_{in} - V_{DS1}) \times D - V_{DS2} \times (1-D) - I_L \times R_L \quad (4)$$

A common simplification is to assume V_{DS1}, V_{DS2} and R_L are small enough to ignore. Setting V_{DS1}, V_{DS2} and R_L to zero, the above equation (4) simplifies considerably to:

$$V_{out} = V_{in} \times D \qquad (5)$$

3. Simulink Model Construction of DC-DC Buck Converter

3.1. Open Loop Modeling of DC-DC Buck Converter

The buck converter with switching devices will be considered here which is operating with the switching period of T and duty cycle D [17]. The state equations corresponding to the converter in continuous conduction mode (CCM) can be easily understood by applying Kirchhoff's voltage law on the loop containing the inductor and Kirchhoff's current law on

these two equations (1) and (2) can be equated and solved for V_{out} to obtain the continuous conduction mode buck voltage conversion relationship.

Solving for V_{out}:

the node with the capacitor branch connected to it.

The ON state is when Switch (M1) is ON and Switch (M2) is OFF, the dynamics of the inductor current $i_L(t)$ and the capacitor voltage $v_c(t)$ are given by equation (6).

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}[(V_{in} - V_{out}) - (R_{on1} + R_L) \times i_L] \\ \frac{dv_c}{dt} = -\frac{1}{c}(i_L - i_{out}) \\ V_{out} = R_{ESR}(i_L - i_{out}) + v_c \end{cases} \qquad (6)$$

The OFF state is when Switch (M1) is OFF and Switch (M2) is ON. The dynamics of the inductor current $i_L(t)$ and the capacitor voltage $v_c(t)$ are given by equation (7).

$$\begin{cases} \frac{di_L}{dt} = -\frac{1}{L}[V_{out} + (R_{on2} + R_L) \times i_L] \\ \frac{dv_c}{dt} = \frac{1}{c}(i_L - i_{out}) \\ V_{out} = R_{ESR}(i_L - i_{out}) + v_c \end{cases} \qquad (7)$$

These equations (1) and (2) are implemented in Simulink as shown in figure 4 using multipliers, summing blocks, and gain blocks, and subsequently fed into two integrators to obtain the states $i_L(t)$ and $v_c(t)$ [18-20].
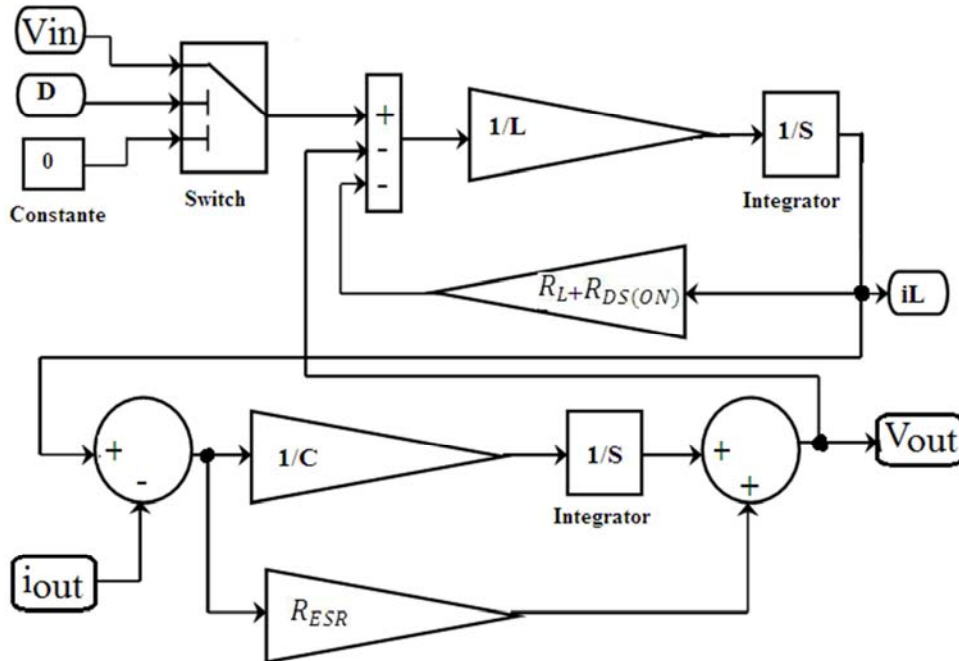

Figure 4. Open –loop modeling of DC-DC buck converter.

3.2. Close-Loop Modeling of DC-DC Buck Converter

The PID controller has several important functions: it provides feedback; it has the ability to eliminate steady state offsets through integral action; it can anticipate the future

through derivative action. PID controllers are sufficient for many control problems, particularly when process dynamics are design and the performance requirements are modest [21].

In order, to get varies desired output voltage there are difficult to tune. The design methods differ with respect to the

knowledge of the process dynamics they require. A PI controller is described by two parameters (Kp and Ki) and a PID controller by three or four parameters (Kp, Ki, Kd, and Ts). In these methods process dynamics are characterized by two parameters. One parameter is related to the process gain and the other describes how fast the process is. In the step response method, the parameters are simple characteristics obtained from the step response. In the frequency response method, the parameters are the ultimate gain and the ultimate frequency [22]. By tuning the three constants in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation [23].

The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining u(t) as the controller output, the final form of the PID algorithm is:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{d}{dt} e(t) \qquad (8)$$

Figure 5 shows close loop modeling of DC-DC buck converter with PID controller.
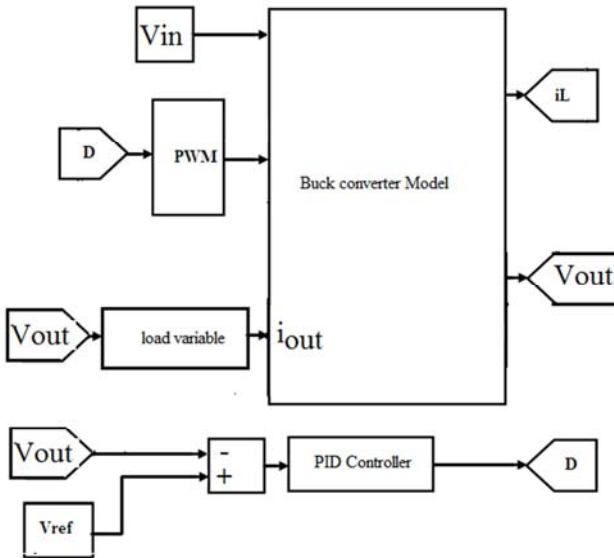

Figure 5. Close –loop modeling of DC-DC buck converter with PID.

4. Results and Discussion

In this section, simulation results for synchronous buck converter circuit without controller and buck converter with PID controller. The results are based on output voltage rise time, peak time, and settling time. The simulation of the converter controlled with PID controller had been test with variation ranging from 0.5 Volt to 3.3 Volt.

Table 1 shows the specifications parameter of DC-DC synchronous buck converter.

Table 1. Buck converter parameter.

Parameters	Values
Input Voltage	5 volt
Indutor	1μH
Capaitor	22 μF
Ron(M1)=Ron(M2)	300 mΩ
RL	20 mΩ
RESR	60 mΩ
Swithing Frequony	50 MHz

The simulation results of output voltage for buck converter with PID controller and without controller such as input voltage is 5 V are shown in following figures.

The simulation result of output voltage in figure 6 shows that the converter with PID controller lowers the input voltage (5V) to reference voltage (0.5V).
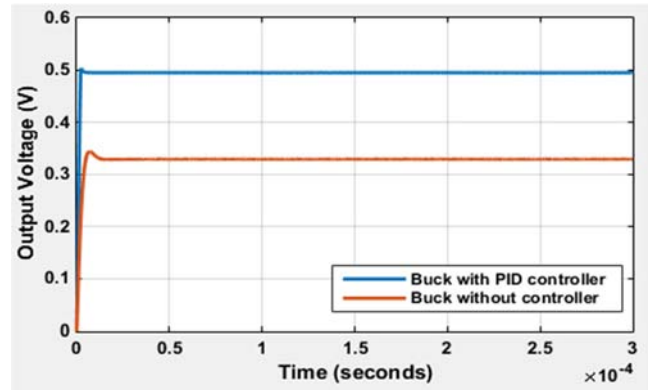

Figure 6. Output voltage when Vref set to 0.5 Volt.

In figure 7, the simulation result shows that the output voltage of the converter with PID controller go to 2 V (reference voltage value) from 5 V (input voltage).
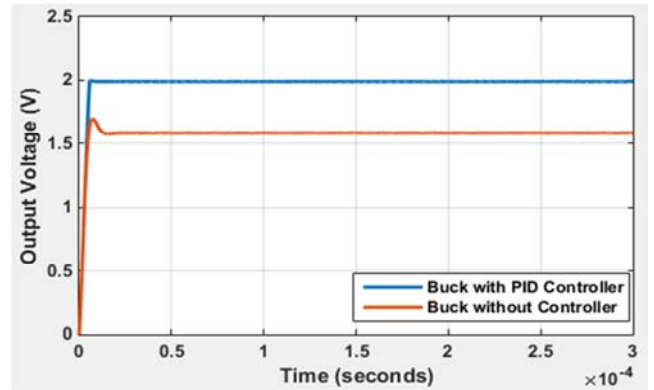

Figure 7. Output voltage when Vref set to 2 Volt.

Figure 8 shows that the output voltage of the converter with PID controller is 3.3V (reference voltage value) from 5V (input voltage).
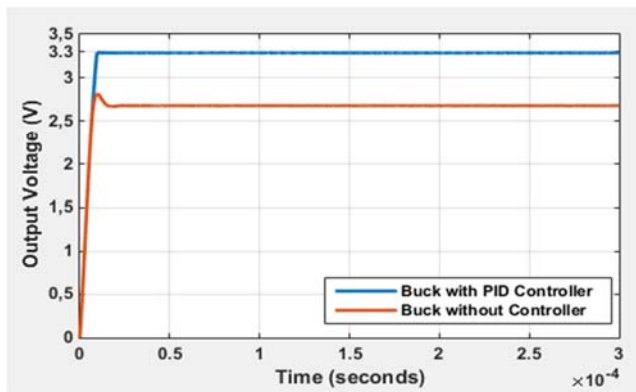
Figure 8. Output voltage when Vref set to 3.3 Volt.

5. Conclusion

This paper has provided a brief overview of the operation of a buck DC-DC converter, the mathematical model is derived from the system equations and provides an accurate representation of the buck Converter. The MATLAB/SIMULINK is also used for modeling and simulation of DC-DC converter.

As conclusion, the converter with PID Controller gives very good dynamic respond in order to achieve desired output voltage values for buck converter

Good behavior of the buck converter proves the robustness of the controller especially it shows good stabilization quality.

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