Designing, Simulation and Implementation of current mode control Boost Converter

Shivang Singh[1] & Kevin Nguyen[2]
Electrical Engineering Department, San Jose State University
San Jose, California, USA
[1]shivang.singh@sjsu.edu
[2] kevin.a.nguyen@sjsu.edu

Abstract — Obtaining changes in the output voltage of Boost converter under variable load conditions is a major challenge in industrial applications nowadays. This paper will provide an insight of using peak current mode control for a Boost Converter. We have tried to minimize the ill- effects due to harmonic oscillations. Modeling of Boost Converter along with its designing approach, with Peak current mode is also discussed and validated. The design is simulated in MATLAB software and tested. The experimental results are provided with Boost Converter operating at input voltage of 8V to 10V and 20V output.

Keywords: Peak current mode control, State space analysis, Subharmonic Oscillations, current mode control (CMC).

I. Introduction

In today's fast moving digital world, power supply plays the most important role for it to run. Inside power supply world, we have a Boost Converter, which is a DC-to-DC Power Converter, which increases the voltage coming from the input source to its load at the output portion. It is highly used in several applications including hybrid vehicles, in power systems for achieving higher output voltages than the applied inputs, in inverter systems used in wind energy turbines and many more [1]. A Boost Converter belongs to the class of Switched Mode Power Supply (SMPS), which makes usage of at least two semiconductors and at least a power saving element, such as a capacitor.

As microprocessors and digital signal processors demand higher current at even lower operating voltages, it gets much critical to minimize the power supply conduction losses by making the resistance of the current sensing element as low as possible [2].

Current-mode is a multiple loop-control method which contains two loops, unlike voltage control with just one loop. There are multiple methods within current mode control methods, but Peak current mode control is the most popular one among all. This technique is called as Current Mode Control, since in it, the Inductor Current is directly controlled and the output voltage is controlled indirectly by current loop. Also here we use a reference voltage to maintain the dynamics of the circuit [3].

In current mode control, the current loop gets the peak current limit with respect to the outer loop of the voltage. The peak current limit for the outer loop was directly proportional to the average current which is required to maintain the desired output voltage, which is the basic functionality of the Boost Converter. But there remains a chance of non-stability, which starts when the duty cycle gets greater than 50% value. We can judge the instability in the form of subharmonic oscillations which ultimately leads to poor output regulation. To overcome this side-effect of subharmonic oscillations, we added an external ramp which damps out subharmonic oscillations in the inductor current.

To observe the behavior of our Boost Converter, a mathematical modeling and its observation has been performed in the paper. We have utilized the state space approach to study the small signal behavior for the Boost Converter.

This paper will present the mathematical modeling and a design implementation of the current mode control Boost Converter. Also along with it, the peak current method modelling and the power load mechanism along with loop analysis is done. The experiment and simulation results are also provided in the paper as we move ahead.

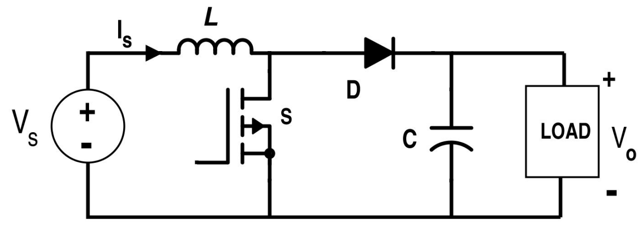

Figure 1. A General Boost Converter

We can use a sawtooth ramp for controlling the duty cycle of the Boost converter, but the easiest and the simplest way to regulate the peak inductor current is with a control signal V_c [4]. If we go on to use the sawtooth signal for controlling of the duty cycle, we may increase the noise immunity. The circuit for a Boost Converter with current-mode control is also shown as below :

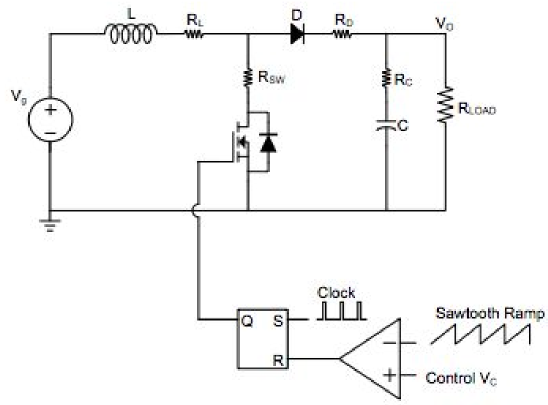

Figure 2. A Generalized Boost Converter with current mode control

II. Basic Operation of Boost Converter

The Boost Converter works on the principle that it increasing the input voltage to the desired voltage level at the output. The constitution of a Boost Converter consists of an inductor L, a capacitor C, a switch S and a diode D. The total amount of time period is T_s, for which the switch runs. The output voltage V_o is higher than the input voltage V_s.

The Boost Converter belongs to the family of indirect energy transfer converters. The power process involves an energy-storing phase and an energy-releasing phase. During the ON time, the inductor stores energy and the output capacitor alone powers the load at the output. At the switch opening, the stored inductive energy appears in series with the input source and contributes to supply output.

Boost Converter operates in two different states on the basis of switch state. When the switch is ON, the inductor L is connected to the source (V_s) and the current in the inductor increases in a linear pattern. Also the diode D is reversed biased due to more voltage at the output side. Capacitor C contains the output voltage with it V_o. The equivalent circuit when the Switch is ON, is shown in Fig. 3 below.

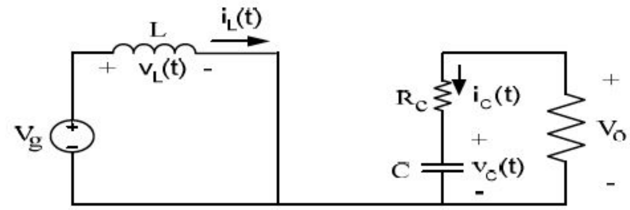

*Figure 3. Boost converter when Switch is **ON***

When the switch of the Boost Converter is OFF, the load at output is connected to the inductor and the source. The stored energy in the inductor now starts getting discharged through diode at the load side. During this period, the inductor current will decreases until the next cycle starts. The circuit for OFF switch is shown in Fig. 4.

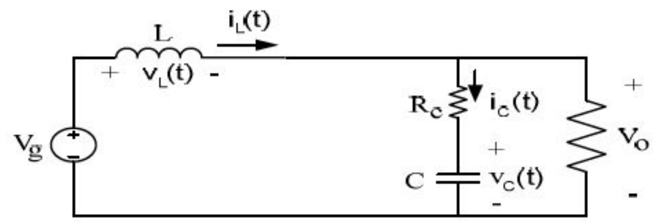

*Figure 4 . Boost converter when Switch is **OFF***

III. Modeling of Boost Converter

From the Figures 2 and 3, we are going to model the Boost Converter in the following steps one by one. We used State Space Modelling Method to obtain the values of V_o, and the Transfer Functions.

The first order equations are as below -

$$\frac{di_L(t)}{dt} = \frac{V_g}{L} \quad .....(1)$$

$$\frac{dv_C(t)}{dt} = -\frac{1}{C(R+Rc)}v_C(t) \quad .....(2)$$

$$v_o(t) = \frac{R}{R+R_C}v_c(t) \quad .....(3)$$

These are the generalized equations. We can see the circuit for ON state in Fig. 2 and the equations when the switch is turned ON are as below-

$$\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dv_C(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C(R+R_C)} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_g \quad .....(4)$$

$$v_0(t) = \begin{bmatrix} 0 & \frac{R}{R+R_c} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} \quad \text{..... (5)}$$

The inductor current and the capacitor voltage are given by the following equations respectively:

$$\frac{di_L(t)}{dt} = -\frac{1}{L}\left(\frac{R.R_C}{R+R_C}\right) i_L(t) - \frac{1}{L}\left(\frac{R}{R+R_C}\right) v_C(t) + \frac{V_g}{L} \quad \text{.....(6)}$$

$$\frac{dv_C(t)}{dt} = \frac{1}{C}\left(\frac{R}{R+R_C}\right) i_L(t) - \frac{1}{C}\left(\frac{1}{R+R_C}\right) v_C(t) \quad \text{.....(7)}$$

$$v_o(t) = \frac{R.R_C}{R+R_c} i_L(t) + \frac{R}{R+R_c} v_C(t) \quad \text{.....(8)}$$

From the above stated equations we can convert into the State Space form as illustrated below:

$$\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dv_c(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}\frac{R.R_C}{R+R_C} & -\frac{1}{L}\frac{R}{R+R_C} \\ \frac{1}{C}\frac{R}{R+R_C} & -\frac{1}{C(R+R_c)} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_g \quad \text{.....(9)}$$

$$v_O(t) = \begin{bmatrix} \frac{R.R_C}{R+R_C} & \frac{R}{R+R_c} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} \quad \text{.....(10)}$$

$$\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dv_C(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}\frac{D'.R.R_C}{R+R_C} & -\frac{1}{L}\frac{D'.R}{R+R_C} \\ \frac{1}{C}\frac{D'.R}{R+R_C} & -\frac{1}{C(R+R_c)} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & \frac{1}{L}\frac{D'.R.R_C}{(R+R_C)} \\ 0 & -\frac{1}{C(R+R_c)} \end{bmatrix} V_g \quad \text{.....(11)}$$

$$v_0(t) = \begin{bmatrix} \frac{D'.R.R_C}{R+R_C} & \frac{R}{R+R_c} \end{bmatrix} \quad \text{.....(12)}$$

After doing Perturbation, we use the following constraints for our equations :

$$\widehat{D} = D + \hat{d}$$

$$i_L = I_L + \hat{\imath}_L$$

$$\hat{v}_C = V_C + \hat{v}_C$$

$$\hat{v}_o = V_0 + \hat{v}_0 \quad \text{.....(13)}$$

Using them in our equations, we obtain the following equations:

$$C(R+R_C)\frac{d\hat{v}_o(t)}{dt} = R.D'.i_L(t) + \frac{(R+R_C)V_g}{D'(R_C+D'R)}\hat{d}(t) - \widehat{v_O}(t) \quad \text{.....(14)}$$

$$L(R+R_C)\frac{di_L(t)}{dt} = -R.R_C.D'.\widehat{\imath_L}(t) - \frac{(R+R_C)V_g.\hat{d}(t)}{D'} - R.D'.\widehat{v_O}(t) \quad \text{.....(15)}$$

The output Transfer Function is given as using Small Signal Model for the equations 14 and 15:

$$G_{vd}(s) = \frac{\hat{v}_O(s)}{\hat{d}(s)} =$$

$$G_{vd}(s) = \frac{\frac{V_g}{(RD'+R_C)D'}(R^2.D'^2 - s(R+R_C)L)(1+sCR_C)}{\frac{RD'(RD'+R_C)}{R+R_C} + s(L+RR_C.D'.C) + s^2LC(R+R_c)} \quad \text{.....(16)}$$

The final equation is obtained as the following:

$$G_{id}(s) = \frac{\hat{\imath}_L(s)}{\hat{d}(s)} \quad \text{.....(17)}$$

$$G_{id}(s) = \frac{\frac{V_g}{D'}\left(1 + \frac{RD'}{(RD'+R_C)} + s((R+R_c)C)\right)}{\frac{RD'(RD'+R_C)}{R+R_C} + s(L+R.C.D'.R_c) + s^2(R+R_c)LC}$$

IV. Current Mode Controlling

In order to apply Current Mode control, we have several pre-requirements in our system. We want to obtain a good output voltage, with the condition of having a continuous variable load. Current Mode Control is beneficial than the Voltage Mode Control since it utilizes the current of the inductor to manage the output voltage and not the voltage of the capacitor. Current Mode Controlling operates in a two loop. The current from the outer voltage loop is compared with the inductor current. The switching ON and OFF of the switch is managed by providing a Duty Cycle which is generated by a frequency and the switch gets turned ON at a constant frequency and turned OFF once it senses that the current magnitude has crossed a fixed reference value of current.

We are using the Peak Current Control Mode rather than the Average current mode control, since in average control mode, the average inductor current is controlled while in the peak current mode control, the peak inductor current is controlled by using a output voltage.

V. Peak Current Mode Control Of Boost Converter

Peak Current Mode Control is a very popular current-mode control technique, for controlling the output voltage. It uses a Duty Cycle to manage the frequency clock. The Duty Cycle is stopped when the inductor current reaches a fixed reference value. A generalized Boost Converter with Peak Current Mode Control is shown in the Figure 2.

The transfer function for the output value is calculated from the equations 16 & 17, which are the standard equations for $G_{vd}(s)$ and $G_{id}(s)$. We can obtain the following equations by solving these two Transfer Function equations, which relate to the Boost Converter:

$$A = \frac{\widehat{v_o}}{\widehat{v_c}} = K_{dc} * f_p * f_h \text{ ; where}$$

$$(DC\ Gain)\ K_{dc} = \frac{(1-D)R}{R_i};$$

$$(Power\ stage\ TF)\ f_p = \frac{\left(1+\frac{s}{\omega_z}\right)\left(1-\frac{s}{\omega_{rh}}\right)}{\left(1+\frac{s}{\omega_p}\right)};$$

$$(High\ Frequency\ TF)\ \ f_h = \frac{1}{\left(1+\frac{s}{\omega_n Q_p}+\frac{s^2}{\omega_n{}^2}\right)}$$

Further the values of sub-units used in above formulas include the value of zero of capacitor, RHP Zero and Pole, which are stated as below :

$$Capacitor\ Zero, \omega_c = \frac{1}{C*R_c};$$

$$RHP\ Zero, \omega_{rh} = \frac{R*(1-D)^2}{L};$$

$$Pole, \omega_p = \frac{2}{CR};$$

Moreover the value of the Damping Factor is given as :

$$Damping\ Factor, Q_p = \frac{1}{\pi * (m_c * (1-D) - 0.5)}$$

$$;where\ m_c\ is\ the\ compensation\ ramp\ factor$$

Also we have multiple other advantages of using the Current Mode Control, since in it the LC filter resonance and the subharmonic oscillations are removed and the system remains a first order system, making designing of the compensator much more simpler.

VI. Comparison Between Voltage Mode & Current Mode Control Of Boost Converter

Voltage Mode Control is one of the two methods of controls for the Boost Converter. As from its name, Voltage Mode Control, also known as Duty Cycle Control, contains a single loop and adjusts the duty cycle directly in response to the output voltage variations [5]. The effects of applying the Voltage Mode Control on our Boost Converter, are huge and can be seen in the plots below.

We observed the following specifications in out Boost Converter when applied with Voltage Mode Current and we can *conclude* several points from the above plots, some of which are as below:

1. The RHP Zero remains the same, no matter which methodology we apply to our Boost Converter.
2. The Current Mode Control Boost Converter is far more easy to compensate.
3. In the gain, we have a sudden spike and then the gain downfalls tremendously while in Current mode control its moving at a compared steady rate.
4. We have much more Phase Margin in the Current Mode Control Boost converter as compared to the Voltage Controlled Boost Converter.

VII. Simulation Results

The Peak Current Mode Control is implemented on a Boost Converter. The Simulink model can be seen in the Figure 5.

The current mode control is implemented with the following specifications in consideration -

Input Voltage, V_i = 9 V to 11 V
Output Voltage, V_o= 20 V
Load, R = 10 Ω
Inductor, L = 135 mH
Filter Capacitor, C = 120 μF
Feedback Gain, R_i = 35 mΩ
Capacitor, R_c = 1mΩ
Switching frequency = 20 KHz

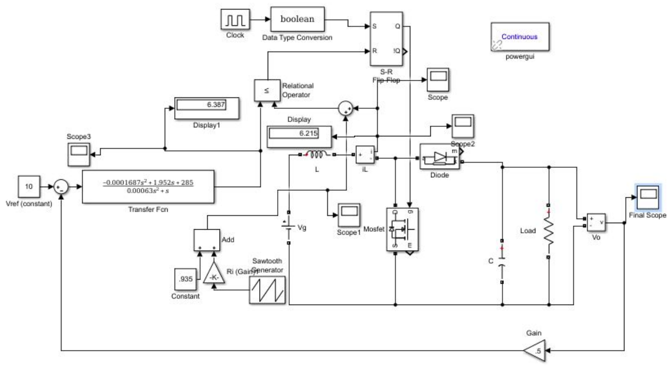

Figure 5. Simulink Model of the Boost Converter with Current Mode Control Method

The Bode Plot of the Magnitude in Gain and the Phase is being shown in Figure 6. The inductor current has two forms in Figure 7 & 8. The Output Voltage is being seen in Figure 9.

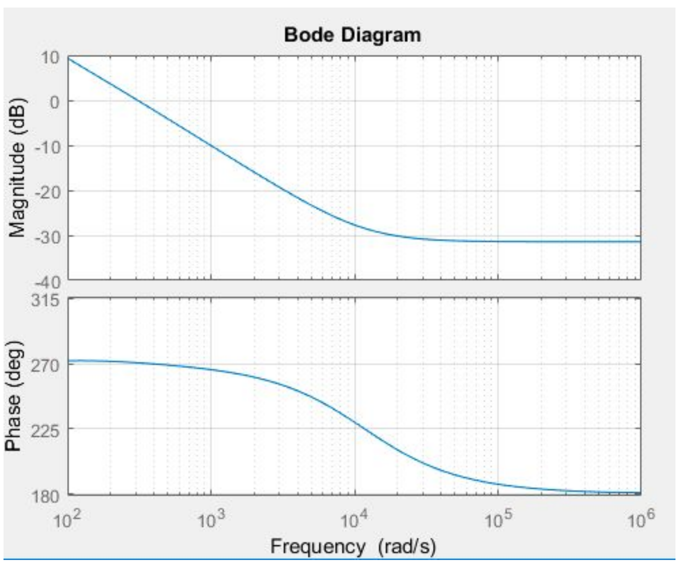

Figure 6. Bode Plot showing the Gain and Phase with Current Mode Control of Boost Converter

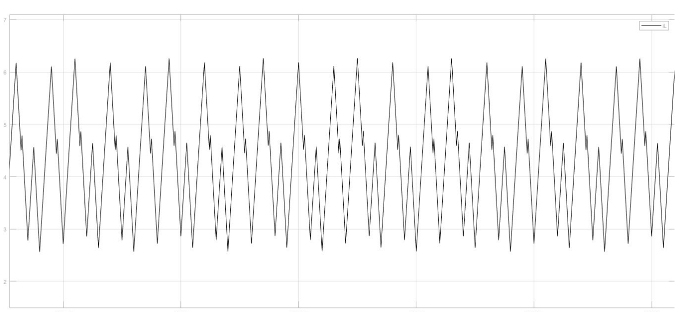

Figure 7. Inductor Current

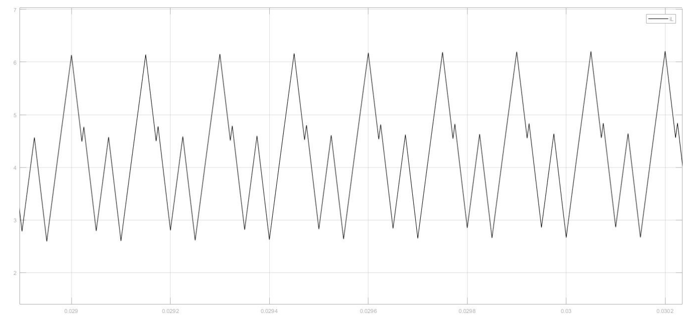

Figure 8. Zoomed view of Inductor Current

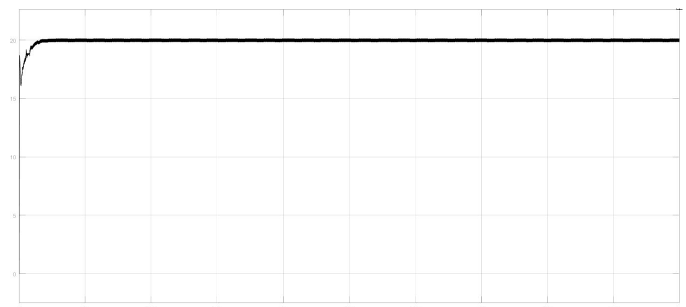

Figure 9. The Output Voltage, being countered to value of 20 Volts

The peak current mode has been implemented with the help of MATLAB software. It has been performed in the Engineering Laboratory of San Jose State University, California.

VIII. Advantages Of Peak Current Mode

There are multiple advantages of using Peak Current Mode Control for controlling the output voltage, over using the technique of Voltage control Mode on the Boost Converter. Some of the advantages of Current-Mode Control over Voltage Mode Control are stated as below:

1. There is a huge Reliability while implementing the Current mode control, when there is a quick operation for overload condition and the short circuit condition; while the voltage controlled mechanism is a bit slower to react for the alarming situation of over-current.
2. It has a much simpler feedback loop compensation, allowing the system to remain stable.
3. It is easy and has accurate current sharing in multiphase designs.

4. It makes the order of the system lower, than compared to the voltage mode controlled mechanism.
5. Current Mode Control also eliminates the subharmonic oscillations, making a pathway for good output voltage result.

IX. Possible Future Scopes

- We can replace all the MOSFETS with a straight parallel integrated IGBT, to reduce the price and save money, with the condition of maintaining the same switching frequency [6].
- The switch can be made self active-clamp, for making a much more cheaper and high performing boost converter operating with current mode control.

X. Conclusion

Compensation for current-mode boost converter is much easier than voltage-mode boost converter, even if the RHP zero is at a low frequency. The Type II compensation has simple design rules, and good stability is usually achieved on the first attempt. There is no minimum requirement for the crossover frequency, so you can always make the system stable regardless of the RHP zero frequency. The current loop eliminates the ringing frequency of the filter, and good performance is achieved even with a relatively low crossover frequency on the voltage feedback loop [7]. Simulation of the current-mode boost converter gives us these results, and reveals the importance of such a control method in industry [8].

XI. Acknowledgement

We would like to thank our Professor Mohamed Badawy, for giving us the opportunity to work on this industry-oriented topic and also helping us whenever we needed any guidance and got stuck with some problems.

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