

Control of Boost type Converter in Discontinuous Conduction Mode by Controlling the Product of Inductor Voltage-Second

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Abstract: Battery-operated systems such as cell-phone, digital camera become more and more popular. In these applications, a boost-type converter is usually required to convert low battery voltage to higher voltage. In this paper, a variable frequency control of boost converter is discussed. The prototype circuit is built to prove the concept. The extension of this approach in Power Factor-Correction application is discussed.

I INTRODUCTION

Battery-operated systems such as digital camera, TFT-LCD bias supplies, require a boost converter to step up the low battery voltage to higher voltage. For these applications, it is very important to extend the battery life. Therefore, efficiency is critical even at light load condition. Fixed frequency PWM control is very popular. Two items related to PWM boost converter is a concern for customers. First, if the boost converter is operated in the continuous-conduction mode (CCM), there is a right half plane zero, which is difficult to be stable. The discontinuous conduction mode is desired for low power application. Second, at light load, boost converter is difficult to regulate because PWM controller typical has certain minimum on time and the on time of switch at fixed frequency will keep pumping energy to output and it will cause over voltage at very light load or no load condition.

In this paper, another approach is investigated. This approach controls the boost converter always in discontinuous conduction mode by forcing the product of inductor voltage-second to be zero in each switching cycle. By doing so, the stability of system is always guaranteed and no compensation network is required. In addition, the proposed control has natural power limit and will prevent the boost converter from being over stressed by over load. Since it operates in variable frequency, at light load, the frequency is very low and it helps regulate the output voltage as well as offer better efficiency since low switching loss is resulted. The concept can be implemented by sensing inductor current or switching current with an integrator. One extension of the approach to control of Power Factor Correction is also proposed. The experimental result is provided to prove the concept.

II PROPOSED CONTROLLER FOR BOOST CONVERTER WITH INDUCTOR CURRENT SENSING

The proposed controller for boost converter with inductor current sensing is shown in Figure 1.

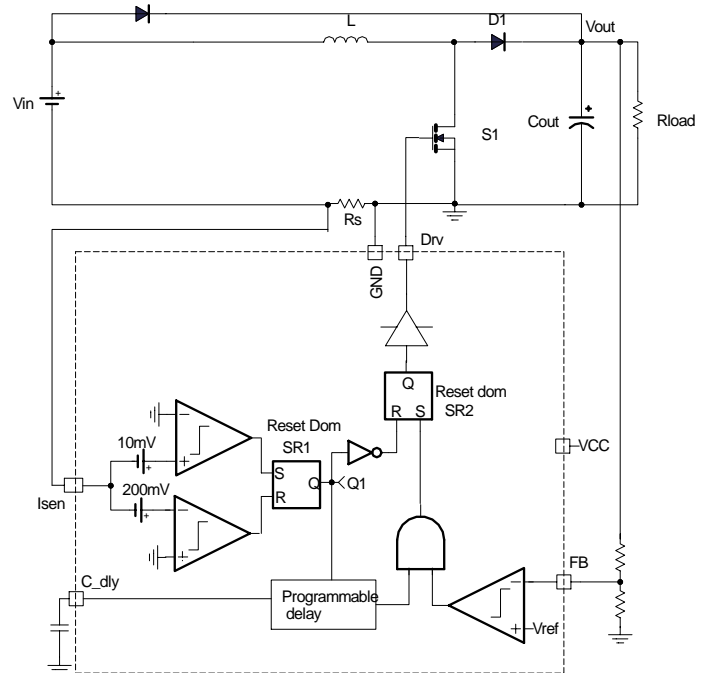


Figure 1. Proposed control approach diagram for a boost converter.

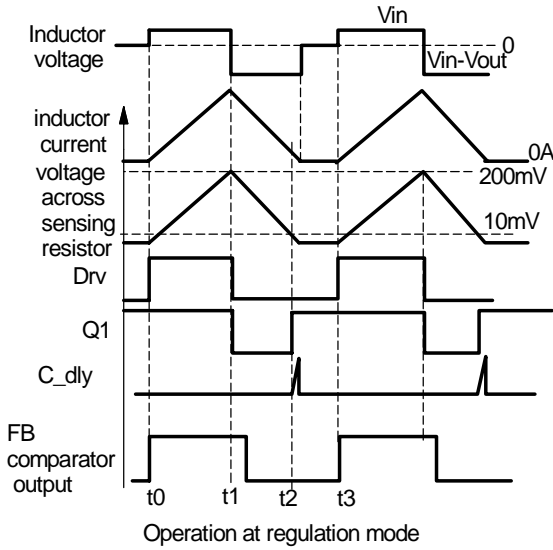


Figure 2. Operation waveforms at regulation mode.

This control has two operation mode, regulation mode and power limit mode. At regulation mode, the waveform is shown in Figure 2. The inductor operates at discontinuous conduction mode and the output voltage is regulated at desired output voltage

1. Regulation Mode

The operation concept is as follows.

First, during time t0~t1, Latch SR2 outputs logic High and the switch is on. The inductor current linearly increases from zero. When the voltage at sensing resistor Rs reaches the current threshold V_{IL_TH} for example 200mV, Latch SR1 and SR2 are reset to zero. The switch is turned off at t1. The inductor voltage is given as

$$V_L(0 \sim t_1) = V_{IN}$$

The peak inductor current is given as

$$i_{L_peak} = \frac{V_{IN}}{L} \times t_1 \text{-----(1)}$$

The peak inductor current is limited by the current threshold V_{IL_TH} and current sensing resistor.

$$i_{L_peak} = \frac{V_{IL_TH}}{R_s} \quad \text{where } V_{IL_TH} = 200mV \text{---(2)}$$

Combination of above two equations results in

$$t_1 = \frac{V_{IL_TH} \times L}{R_s \times V_{IN}} \text{-----(3)}$$

From t1 to t2, the inductor current decreases. Before the voltage across the sensing resistor reaches 10mV, the output of latch SR1 keeps low and switch holds off. At time t2, the voltage across current sensing resistor reaches 10mV and the inductor current decreases to almost zero, the latch Sr1 is set

to High. This will enable the SET of latch SR2 to be controlled by feedback comparator. If we neglect 10mV, the inductor current reduced to zero at t2. The voltage across the inductor is

$$V_L(t_1 \sim t_2) = V_{IN} - V_{OUT}$$

The following equation exists based on inductor voltage-second balance.

$$V_{IN} \times t_1 + (V_{IN} - V_{OUT}) \times (t_2 - t_1) = 0$$

$$t_2 - t_1 = \frac{V_{IN}}{V_{OUT} - V_{IN}} \times t_1 \text{-----(4)}$$

From t2 to t3, the output voltage is discharged through output load until the output voltage is below reference voltage. At t3, the FB comparator goes high and SET the latch SR2. Switch is ON again and another cycles starts. The programmable delay is added as an option to ensure the inductor current goes to zero.

Since the inductor current reaches zero in each cycle, the input power will be the energy stored in the inductor divided by switching period.

The input power is given as

$$P_{IN} = \frac{\frac{1}{2} \times L \times i_{L_peak}^2}{T_s} \text{-----(5)}$$

where Ts is the switching period. Substitution of equation (2) into above equation results in

$$P_{IN} = \frac{L \times V_{IL_TH}^2}{2 \times R_s^2 \times T_s} \text{-----(6)}$$

Since the inductor current is discharged to zero in each cycle, the energy stored in the inductor is transferred to the load in each cycle. If assuming the efficiency is 100%, the input power will be equal to output power.

$$P_{IN} = P_{OUT} = V_{OUT} \times I_{OUT} \text{-----(7)}$$

Substitution of equation (6) into above equation results in

$$F_s = \frac{2 \times R_s^2 \times V_{OUT} \times I_{OUT}}{L \times V_{IL_TH}^2} \text{-----(8)}$$

where Fs is the switching frequency and $F_s = \frac{1}{T_s}$.

Since at regulation mode, the output voltage equals nominal output voltage.

$V_{OUT} = V_{OUT_nom}$. The equation (8) can be written as

$$F_s = \frac{2 \times R_s^2 \times V_{OUT_nom} \times I_{OUT}}{L \times V_{IL_TH}^2} \text{-----(9)}$$

The above equation shows that the switching frequency linearly increases when load current goes up.

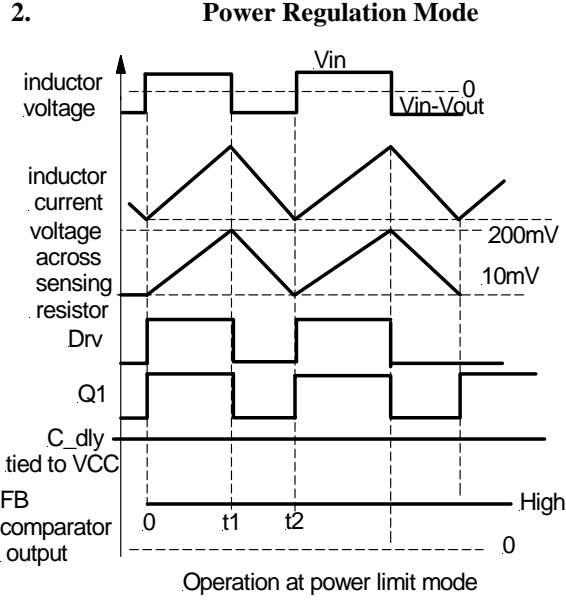


Figure 3. Operation waveform at power limit mode with $C_{ldy}=VCC$

When load current keeps going up, eventually the inductor will operate in the boundary of Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM). The concept of this control is that the switch is turned on only after the inductor current reaches to zero. This concept will limit the maximum power that the input can deliver. When load current is high enough, the output power will reach the input power limit. The output voltage will be no longer regulated and it will keep decrease as load current increase. The operation waveform is shown in Figure 3. At power limit mode, since the output voltage is lower than regulation, the FB comparator output is always high. The switch is simply controlled by the latch SR1 and current sensing comparator. The switch is on when inductor current reaches low threshold such as 10mV and turn off when inductor current reaches high threshold. The average inductor current is given as

$$i_{L_avg} = \frac{1}{2} \times i_{L_pk} = \frac{1}{2} \times \frac{V_{IL_TH}}{R_S} \quad \text{-----(10)}$$

Input power equals output power, therefore
 $P_{IN} = V_{IN} \times I_{L_avg} = P_{OUT} = V_{OUT} \times I_{OUT}$

Substitution of equation (10) into above equation results in

$$V_{OUT} = \frac{V_{IL_TH} \times V_{IN}}{2 \times R_S \times I_{OUT}} \quad \text{-----(11)}$$

The above equation shows that the output voltage will be reduced when output current goes up. The maximum load current with regulated output voltage will be

$$I_{OUT_reg} = \frac{V_{IL_TH} \times V_{IN}}{2 \times R_S \times V_{OUT_nom}} \quad \text{-----(12)}$$

Where I_{OUT_reg} is maximum load output current with regulated output voltage V_{OUT_nom} .

During the power limit mode, the switch period is given as
 $T_S = t_2 = t_1 + (t_2 - t_1)$

Substitution equation (3) and (4) into above equation, we have

$$F_S = \frac{1}{T_S} = \frac{R_S \times V_{IN}}{V_{IL_TH} \times L} \times \left(1 - \frac{V_{IN}}{V_{OUT}}\right) \quad \text{-----(13)}$$

Substitution of equation (11) into above equation results in

$$F_S = \frac{1}{T_S} = \frac{R_S \times V_{IN}}{V_{IL_TH} \times L} \times \left(1 - \frac{2 \times R_S \times I_{OUT}}{V_{IL_TH}}\right) \quad \text{---(14)}$$

The above equation shows that the frequency will decrease when load current increases. Overall, the relationship between output voltage, frequency and load current is shown in Figure 4. The peak frequency occurs at the transition between regulation mode and power limit mode. At transition time, $V_{OUT} = V_{OUT_nom}$

Substitute of above equation to equation (13) results in the maximum operation frequency

$$F_{S_max} = \frac{1}{T_S} = \frac{R_S \times V_{IN}}{V_{IL_TH} \times L} \times \left(1 - \frac{V_{IN}}{V_{OUT_nom}}\right) \quad \text{-----(15)}$$

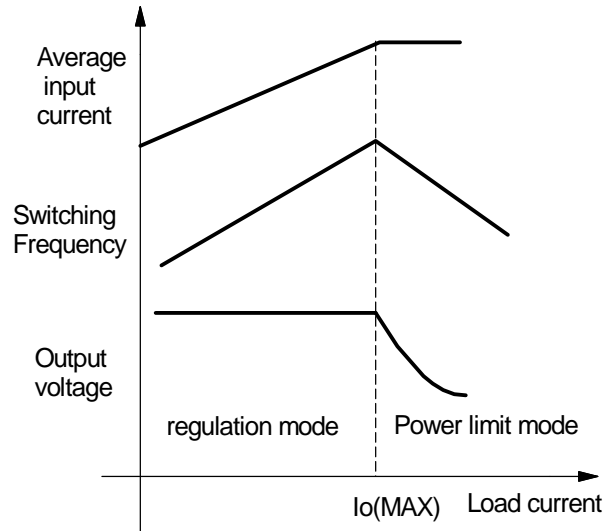


Figure 4. Theoretical characteristics for the boost converter with proposed control approach.

With this control approach, at each cycle, the voltage-second product of inductor is always reset to zero and inductor current always goes to zero before another cycle starts. Ideally, the threshold voltage to ensure inductor current decreases to zero should be 0mV. However, in reality, since comparator has offset and 10mV is used to

compensate the comparator offset. Additional delay can be generated by putting extra cap at “C_dly” pin. The programmable delay is to ensure inductor current fully going to zero before other cycles starts

. From equation (3), the switch ON time is fixed if the input voltage is fixed, the operation principle will be similar to constant on-time control and the output voltage is regulated by changing the off time and switching frequency. The characteristics of this control is shown in Figure 4. Before load current reaches critical current $I_o(MAX)$, the output voltage is regulated to desired output. The switching frequency increases as load current increases. At light load, the switching frequency can be very low and efficiency is high comparing to fixed PWM control. This feature is usefully for battery-operated application because of energy saving at idle mode. When load current keeps increasing and inductor current starts to operate at the boundary of Discontinuous and Continuous mode due to the nature of control. The system goes into power limit mode as shown in Figure 3. In this mode, the average inductor current is fixed and output voltage starts to goes down as load current increases. And the switching frequency also goes down due to longer turn off time. This control approach has natural power limit, which is useful at over load condition as well as soft start. Overall, the following features is summarized as

- Variable frequency control. At light load, frequency goes down and system efficiency is relatively high. This is beneficial for battery operated systems
- System is self stable, no output loop compensation network required.

- Natural current limit. No soft start is required since the output starts up with limited power.
- Switch turns on at zero current results in low switching loss.
- Simple implementation and easy to be integrated into IC.

The drawback of the proposed control is that the output and the input do not share a common ground. This can be relieved by putting the inductor sensing resistor in series with inductor as shown in Figure 5. This requires high-speed differential comparator and it is limited to low input voltage application as well. But it will be a good choice for battery operated systems such as white LED driver application.

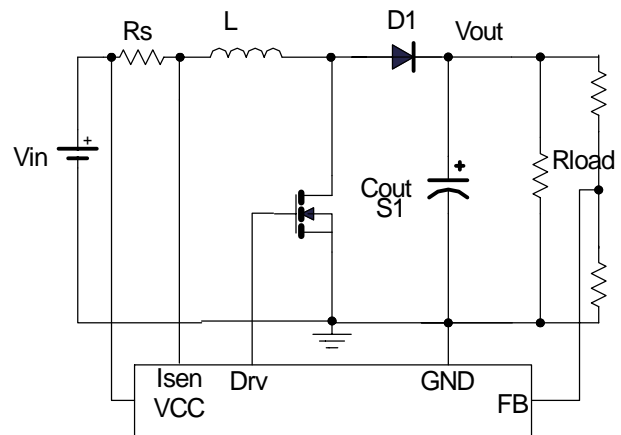


Figure 5. Boost controller with proposed control and differential inductor current sensing.

III EXPERIMENTAL VERIFICATION

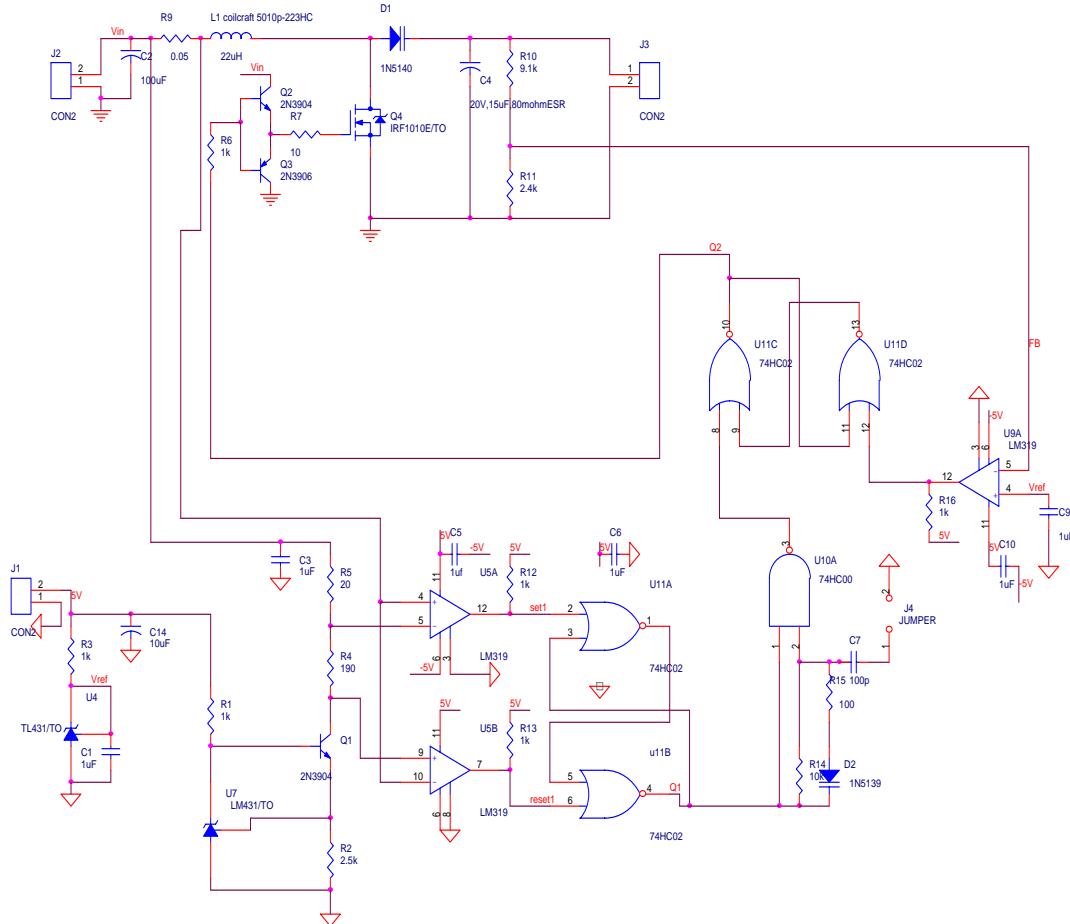


Figure 6. Schematic of a prototype circuit using differential inductor current sensing.

A small power prototype was built to verify the concept. The schematic is shown in Figure 6. The experiment waveforms for start up and normal operation are shown in Figure 7, Figure 8 and Figure 9. The comparison between experimental results and theoretical prediction for output voltage and frequency versus output current is shown in Figure 10 and Figure 11. System specification is as follows: $V_{in}=3.4V$. $V_{out}=12.5V$. $C_{out}=15\mu F$ with 80mohm ESR, Current sensing resistor is $R_s=0.05\Omega$ and input inductance is $L=22\mu H$. The proposed control offers better efficiency at light load, natural current limit and simple implementation.

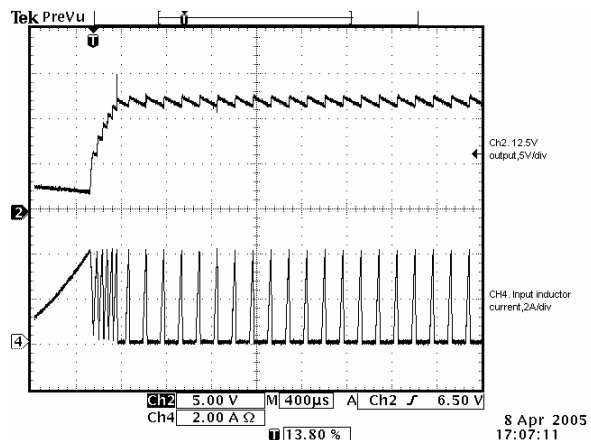


Figure 7. Operation waveforms during the start up.

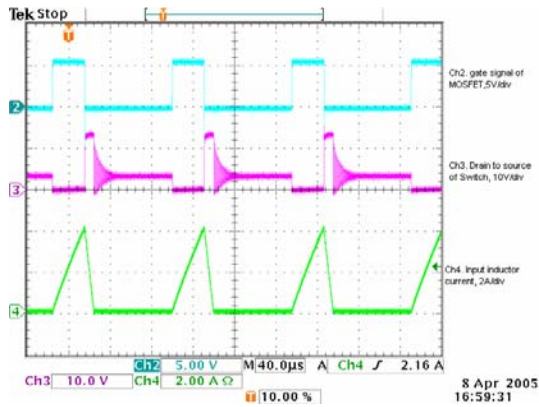


Figure 8. Operation waveforms at regulation mode.

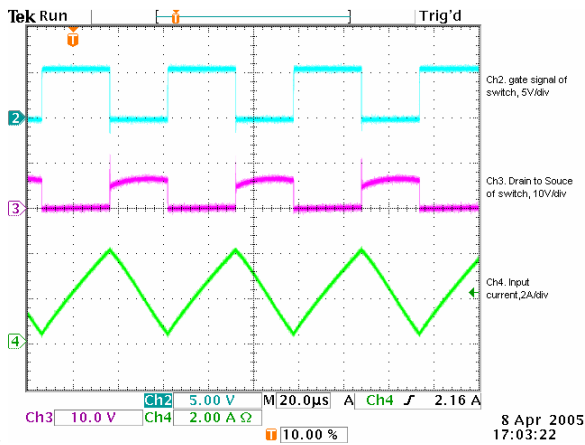


Figure 9. Operation waveform at power limit mode.

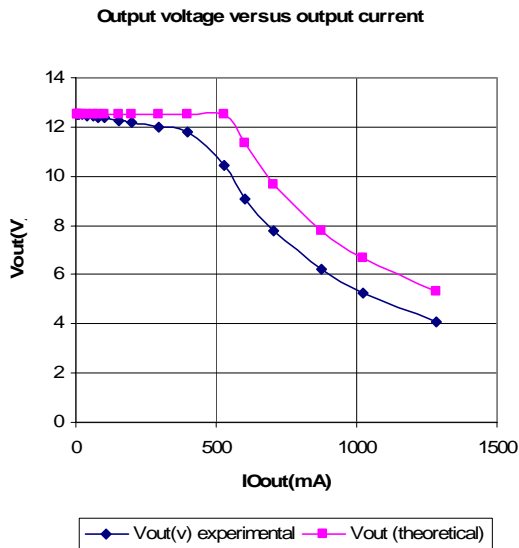


Figure 10. Comparison of output voltage versus output current (theoretical and experimental)

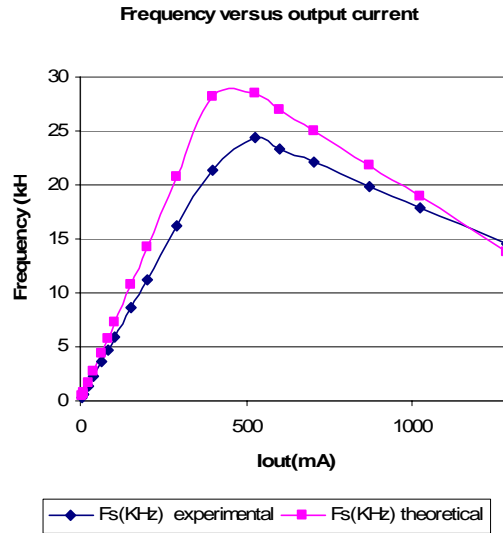


Figure 11. Comparison between experimental results and theoretical prediction for frequency versus output current.

IV EXTENSION I – PWM CONTROL WITH SWITCHING CURRENT SENSING

The proposed concept can be applied to use switching current as well. The basic concept of this approach is to ensure inductor voltage-second going to zero or inductor current going to zero before next cycle starts. This is achieved by using integrator to emulate the inductor current as shown in Figure 12. The operation waveforms are shown in Figure 13. When switch is ON, a capacitor “Cint” is charged by an internal current source that is proportional to $V_{CC}(=V_{in})$. When switching current reaches threshold at $200\text{mV}/R_s$, the switch is turned off. Then the capacitor “Cint” is discharged by current source proportional to $(V_{out}-V_{in})$. Until the capacitor voltage is discharged to a preset voltage such as 200mV , the latches are enabled for SET, which is controlled by the feedback comparator. The capacitor voltage will emulate the inductor current. If the current source voltage coefficients are identical, when the capacitor voltage is discharged to preset voltage, the inductor-second product will go to zero and the theoretical inductor current will go to zero. Figure 14 shows a simulated operation waveform for a 5V to 12V application.

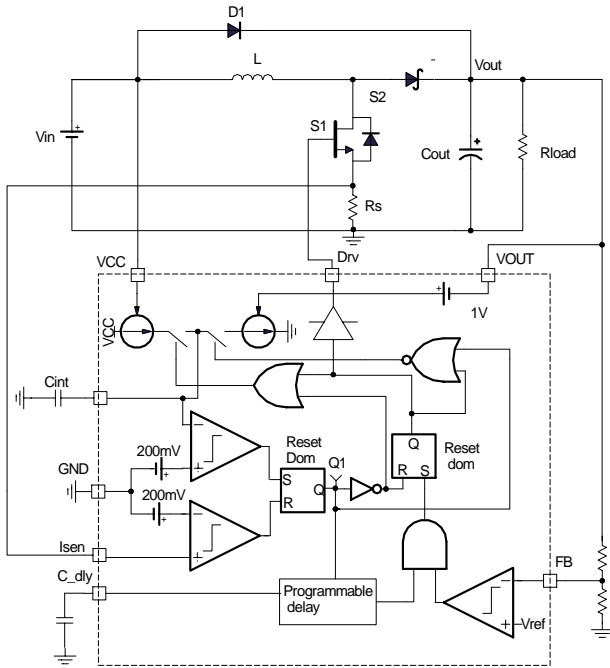


Figure 12. Proposed controller for boost converter with switching current sensing.

Comparing with the approach using inductor current sensing, this scheme offers same feature such as natural current limit and variable frequency control as well as additional features.

- Switching current is sensed. It is convenient for small power application with monolithic IC implementation, where switch is integrated inside IC.
- Sensing switching current will result in lower losses comparing with inductor current sensing.
- Common ground between input and output.

It can be easily extended to buck-boost type converter as shown in Figure 15, with three more features. (1) Output can be either higher or lower than input. (2) The output can be short to ground with current limit. (3) The output can be shut down.

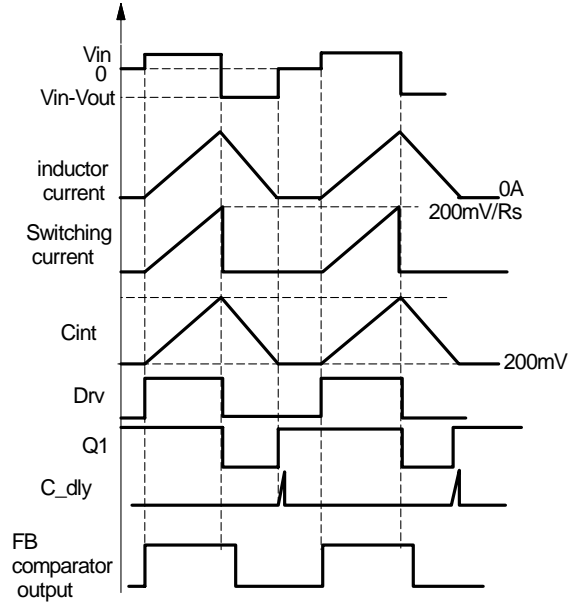


Figure 13. Operation waveforms for proposed control with switching current sensing.

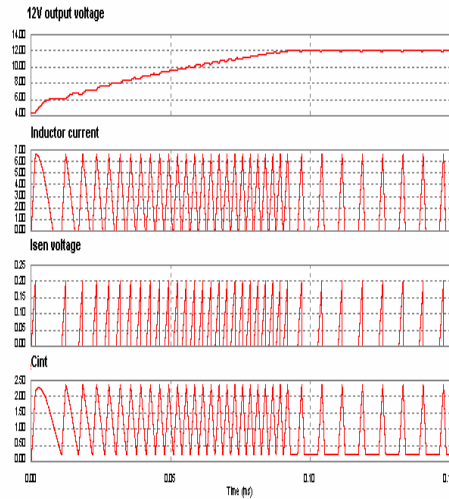


Figure 14. Simulation waveforms for 5V to 12V application with proposed control in Figure 12.

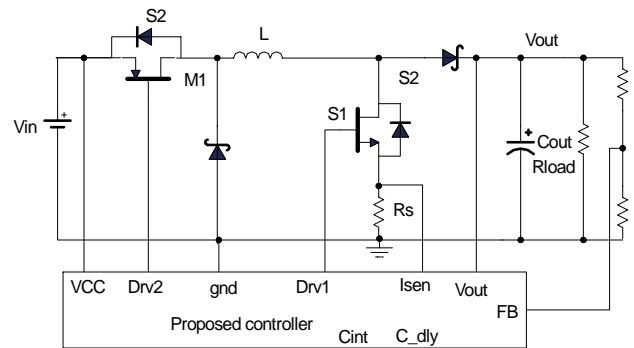


Figure 15. Buck boost converter with proposed controller and switching current sensing.

V EXTENSION II - PFC CONTROL AT BOUNDARY OF DISCONTINUOUS AND CONTINUOUS MODE

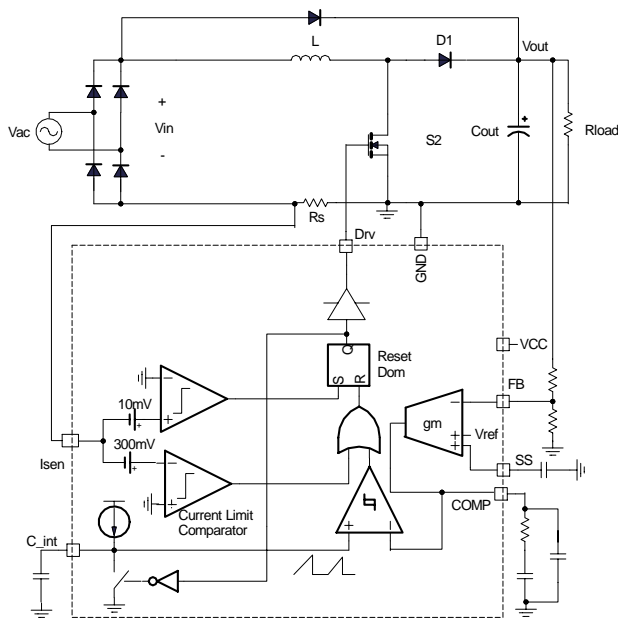


Figure 16. Proposed PFC controller operates in boundary of CCM and DCM.

The same concept can be applied to control PFC (power factor correction). The diagram is shown in Figure 16 and operation waveforms are shown in Figure 17 and simulation result is shown in Figure 18. Instead of using multiplier and sensing input voltage shown in previous article, the on time of switch is controlled by comparing with output of error amplifier and a ramp generated by a constant current source. Since the On time is almost constant during a line cycle if the voltage loop is slow enough, the peak inductor current will be linearly proportional to the input voltage and inductance. The switch is turned on again when the inductor current reaches almost zero ($10\text{mV}/R_s$). By this operation, the inductor current operates in the boundary of Discontinuous Conduction Mode (DCM) and Continuous Conduction Mode (CCM). The average input current will be proportion to input voltage and unit-power-factor is achieved. The load regulation is achieved through modifying the switch ON time by voltage compensation loop. An open loop simulation waveform is shown in Figure 18. Comparing with previous approach such as L6561 from ST, this approach does not require high precision multiplier and no input voltage sensing is required. This is simple and less noise sensitive.

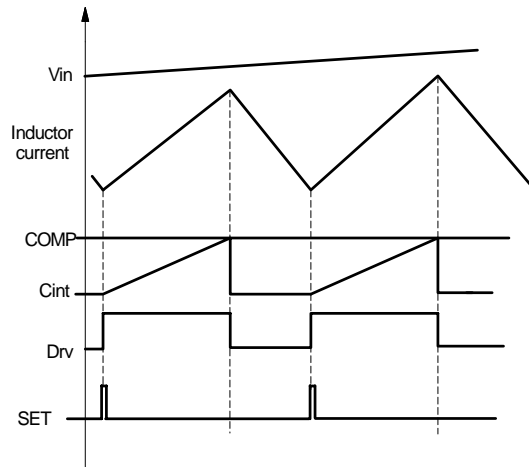


Figure 17. Theoretical operation waveforms for proposed PFC controller..

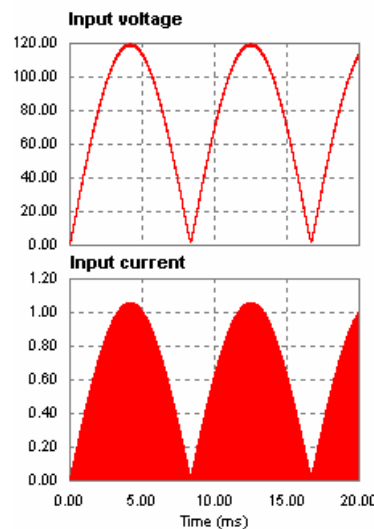


Figure 18. Simulated waveform for a line cycle.

VI CONCLUSION

A new approach to control the boost type converter in discontinuous conduction mode is proposed. This approach offers variable frequency control and natural current limit. Two extensions are derived. One approach uses switching current and an integrator to emulate the inductor current. The other extended approach provides simple PFC control.

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