Integrated Circuit Approach For Soft Switching In Boundary-Mode Buck Converter

Chu-Yi Chiang

Graduate Institute of Electronics Engineering

National Taiwan University

Taipei, Taiwan 10617

binarystar@pelab5.ee.ntu.edu.tw

Chern-Lin Chen

Department of Electrical Engineering
& Graduate Institute of Electronics Engineering

National Taiwan University

Taipei, Taiwan 10617

clchen@cc.ee.ntu.edu.tw

Abstract - An integrated circuit approach is presented for ensuring soft switching operations in boundary-mode buck converters. This technique, accomplished by integrated circuitry, can automatically track the soft switching point without taking energy storage components into account. This control concept may be applied to boost and buck-boost converters as well. Circuit design and simulation results for an example circuit with V_{IN} 5V and V_{OUT} 1.2V are shown.

I. INTRODUCTION

In DC/DC switched-mode power supply, high frequency switching is usually desired to meet the demand of minimizing size and weight. However, high switching losses and noises keep the high switching frequency company. Soft switching techniques [1] have attracted lots of efforts for reducing switching loss and noise. Active clamp [2], asymmetrical half bridge [3-5], and phase-shift full bridge [6-8] etc., have been practically adopted in many commercial products. Soft switching is achieved by taking advantage of the resonance of transformer leakage inductance and power MOS parasitic capacitance. Selection of both of leakage inductance and MOS gating timing is crucial in control design. Managing uniformity of leakage inductance during mass production normally deserves great care.

Soft switching phenomenon under boundary mode operation in buck, boost, and buck-boost converters has been studied [9, 10]. Boundary mode operation provides good stability and fast dynamics. Though the peak current and ripple voltage may go high, it is well suited for many low power applications. Benefits are simple control, easy design, and low cost.

In this paper, a new approach is presented for ensuring soft switching in boundary-mode buck converters. This technique, accomplished by integrated circuitry, can automatically track the optimum soft switching point. No further consideration of the parasitic/leakage components is required. This control concept can also be applied to boost and buck-boost converters.

II. BUCK CONVERTER

Fig. 1. shows the studied integrated buck converter. The power MOS can be either internal or external depending on the cost and thermal considerations. P-type power MOS is usually adopted for S1. If N-type power MOS is used, another charge pump circuit would be needed to drive the power MOS into the triode region. This increases not only the complexity of the circuit but the cost (large chip area of capacitor) of this control IC.

Fig. 1 The studied integrated buck converter

The anti-parallel diode may not exist because it can be eliminated through IC process. If it appears, for certain process, it conducts current I_A when V_{LX} is one diode-drop ($V_D \approx 0.7V$) higher than V_{DD} . This happens when V_{OUT} is higher than half of V_{DD} .

Power MOS S1 is turned on and off periodically and energy is thus transferred from V_{DD} to the output. S1 is off when V_G high and S1 on when V_G low. Fig. 2 shows some important waveforms for a complete switching cycle when inductor current, I_{L1} , works at boundary conduction mode. Freewheeling diode, D1, is used this study and synchronous rectifier may be utilized for enhancing efficiency.

During interval (1), S1 is on, I_{L1} flows directly from V_{DD} to V_{OUT} . V_{LX} is slightly lower than V_{DD} and D1 is off. I_{L1} increases proportional to $(V_{DD} - V_{OUT})$.

During interval (2), S1 is off and I_{L1} flows through D1. V_{LX} is at the level of GND minus V_{D1} ($\sim 0.7V$). I_{L1} decreases proportional to $(V_{OUT} + V_{D1})$.

At the end of interval (2), I_{L1} comes to zero. In interval (3), inductor L1 starts to oscillate with equivalent capacitance, C_{eq} , attached to node V_{LX} . Voltage at V_{LX} then follows the resonance trajectory of L1 and C_{eq} . By the time that S1 turned on again, V_{LX} can be of any value between $-V_{D1}$ and $V_{OUT} + (V_{OUT} - V_{D1}) = 2V_{OUT} - V_{D1}$ through various switching techniques. The ending point of the cycle, when S1 switched on, is denoted " V_{LXS} ". The peak of resonance is denoted as V_{LXZ} .

For each cycle, energy of $0.5 \cdot C_{eq} (V_{DD}^2 - V_{LXS}^2)$ in the equivalent capacitor attached to V_{LX} is dissipated at the next turn-on. It may become a serious problem if converters are operated at high frequencies for the minimization of size and weight. Thus, designers try to turn on S1 when V_{LX} moves as close to V_{DD} as possible. The switching loss is minimized when S1 turned on at the peak of resonance, V_{LXZ} .

Fig. 2. Some key waveforms of boundary mode buck converter

III. CONTROL OF SWITCHING TIMING

Fig. 3 highlights the oscillation waveform V_{LX} in interval (3). A peak detector for V_{LX} detects the peak of V_{LX} and sends a signal to turn on S1. Ideally, without circuit propagation delay, S1 can be turned on exactly at V_{LXZ} . Yet this is not the case for real circuits. There is always propagation delay when signals travel. Therefore, S1 will be turned on when V_{LX} equal to V_{LXZD} , shortly after V_{LXZ} .

The time V_{LX} propagating from V_{LXZ} to V_{LXZD} , denoted as Δt_D , includes all propagation delay in peak detector and other logic circuits. It is defined as the time between V_{LX} reaching its maximum and power MOS S1 being just turned on. If, in steady state, we turn on S1 at V_{LXA} , Δt_D before V_{LXZ} , S1 will be turned on exactly at V_{LXZ} . This can be done by sampling V_{LXZD} , holding it as threshold voltage V_{LXZA} , comparing it with V_{LX} when oscillating in interval (3).

Functional diagram of the proposed control approach is shown in Fig. 4. Inside the dotted lines are internal elements. Integrated P-type power MOS S1 is used. By voltage divider, pin FB senses the condition of V_{OUT} , that is, at light or heavy load. Block ‘Switching “Off”’ sends out the turn-off signal to S1. It is assumed that the converter is designed in voltage mode control. The off signal has no effect on soft switching and will be neglected here. Block ‘Switching “On”’ determines the best timing to turn on S1. SR-latch is composed of NAND gates and is shown in Fig. 5.

Fig. 3. Waveform of V_{LX} while oscillating

Fig. 4. Functional diagram of proposed control

Fig. 5. 3-input NAND gate SR-latch

Unlike typical NAND gate SR-latch, there are three inputs in one NAND gate. When S, SS (abbreviation of soft switching here) and R are all equal to “1”, Q and $\bar{Q}$ (means QBAR, the complement of Q) remains its original state. If S or SS=“0” and R=“1”, $\bar{Q}$ will be switched to “1” first and then Q to “0” no matter what the original states are. If S and SS both are “1” and R=“0”, Q will be switched to “1” and $\bar{Q}$ to “0” later.

Block ‘Switching “On”’ consists of two parts: “Peak Detector” and “Soft Switching”, as shown in Fig. 6. As long as V_{LX} is lower than, say, 0.2V here, both of them will be shut down to avoid malfunction.

In interval (3) and V_{LX} greater than 0.2V, “Peak Detector” is activated. When it detects a peak in V_{LX} waveform, it sends a “0” signal to node “S”, then Q will be “0” and S1 is thus turned on. Because of circuit propagation delay, Q will be “0” when V_{LX} is equal to V_{LXZD} . In steady state, both sub-blocks work. “Soft Switching” samples and holds V_{LXZD} (as V_{LXZA}). It compares V_{LX} and this stored value and sends a “0” to node “SS”. Then, Q will be “0” (S1 turned on) when V_{LX} equal to V_{LXZ} . Soft switching is thus accomplished. “Peak Detector” will have no effect in this state because when a peak (V_{LXZ}) detected, S1 has been changed to another state.

Fig. 6. ‘Switching “On”’ block

Circuits of “Peak Detector” are shown in Fig. 7. It is made up of two comparators, two OP’s, two reset PMOS’s, one NMOS, one capacitor, and one NAND gate SR-latch. A typical peak detector is formed of one OP, one PMOS and one capacitor, as shown in Fig. 8. V_{LX} is buffered by a negative-feedback OP1 so that OP1’s output V_{LXP} will not go under ground level and have enhanced driving ability. Rail-to-rail OP’s and PMOS-input comparators are used here and shown in Fig. 9 and Fig. 10, respectively.

We assume that initially $S=0$, $R=1$, and then $Q=0$. Therefore, S1 is on and V_{LX} is pulled up to almost V_{DD} . After that, “S” is switched back to “1” and sub-block “Peak Detector” can do nothing about the state of S1. Meanwhile, V_{LXP} is equal to V_{DD} and output of CP2 is high. Thus QOP is “0” and QOP_ “1”. M1 and M3 is turned on and output of OP2 is pulled up to V_{DD} . M2 is thus off and capacitor C1 is fully discharged (reset).

When S1 is off ($Q=1$), voltage of V_{LX} goes down to one diode drop below ground level. Because of the limited output swing of buffer, V_{LXP} tracks V_{LX} and stops at ground level as voltage of V_{LX} is under ground voltage. At this moment, S remains at “1” because of the hysteresis of comparator CP1. The output of the other comparator CP2 is at “0” state and NAND gate SR-latch is “reset”. Thus QOP is “1” and QOP_ “0”, making M1 and M3 off and the typical peak detector activated. As energy in L1 runs out, it starts to oscillate with C_{eq} . As V_{LX} reaches its peak, the typical peak detector stores this value as V_{LXZ} on C1. Then V_{LX} moves down and is compared to V_{LXZ} through CP1. Consequently, a peak is detected and S is “0” again (S1 on) when V_{LX} reaches V_{LXZD} .

Fig. 7. Circuits of “Peak Detector”

Fig. 8. Typical peak detector

Fig. 9. Rail-to-rail OP

Fig. 10 PMOS-input comparator

Circuits of “Soft Switching” are shown in Fig. 11. It consists of one sample and hold (S/H) circuit (enclosed by dotted lines), one error amplifier OP1 compensated with one capacitor C1, two comparators, and one pulling PMOS M4. “SS Sampling Logic” means “soft switching sampling logic”. Its output, SSSS (Soft Switching Sampling Switch) controls the sampling switch of S/H circuit.

S/H circuit is composed of one buffer OP2, one sampling switch and one sampling capacitor C2. We use transmission gate as sampling switch so that no data would be lost during sampling. Here, we define that transmission gate is “On” when the applied control voltage is V_{DD} (“1” state).

Fig. 11. Circuits of “Soft Switching”

The 1.1V reference voltage comes from band-gap reference circuit and 4V reference voltage is obtained by voltage divider.

During transient, V_{OUT} is below its desired value and FB below 1.1V, too. The difference between them is further amplified by the error amplifier and its output OFB is pulled up to V_{DD} , say, 5V here. Then, CTL is at low, state through CP1 and M4 is on. Thus, SS is equal to “1” and will not affect the state of S1. Sample and hold circuit samples nothing because soft switching sampling switch “SSSS” is off.

As long as buck converter enters steady state, CTL is high and M4 off. Sample and hold circuit works at this moment. It tracks V_{LXP} and shot down the sampling switch when V_{LX} travels to V_{LXD} . Voltage of V_{LXD} is thus held on C2 and compared to V_{LXP} for later cycles. Soft switching is accomplished through this way.

“SS Sampling Logic” is mainly composed of one falling-edge triggered flip-flop. Some other logic gates are added, as shown in Fig 12.

During transient, CTL is low and so is SSSS. STE remains at the original state “1”. Therefore, sampling switch is off and S/H does not work. Inputs of the flip-flop are disconnected from the master latch.

If steady state entered, CTL is switched to high state and inputs of the flip-flop change to the other state (“0” at the top and “1” at the bottom). For buck converter, if power MOS S1 is on ($Q=“0”$), SSSS is “0” and nothing sampled at this time. Later, S1 is turned off ($Q=“1”$), and SSSS is at high state. Data is allowed to enter the first latch and stopped by the second latch. STE is thus at the same state “1”. Meanwhile, sample and hold circuit starts sampling the voltage of V_{LXP} . After energy run-out of L1, oscillation occurs and sub-block “Peak Detector” detects a peak of V_{LX} , and makes S “0” state. Later, S1 is turned on ($Q=“0”$) when value of V_{LX} equal to V_{LXD} . At this time, SSSS is changed to low state and value of V_{LXD} is held on C2 in S/H circuit as the threshold voltage for coming cycles. SSSS will not be high again until CTL is switched back to “0” to ensure that sub-block “Soft Switching” functions well.

Fig. 12. “SS Sampling Logic”

IV. SIMULATION RESULTS

The speed of “Peak Detector” is crucial in the system performance. A 10 MHz sinusoidal signal with a DC level of 2.5V and increasing amplitude is applied to its input. Simulation results for sub-block “Peak Detector” is shown in Fig. 13. The designed peak detector functions well at such a high frequency.

Shown in Fig. 14 are simulations for the complete system with $L1=10\mu H$, $C0=47\mu F$, and equivalent V_{OUT} at FB is designed as 1.2V. Fig. 14(a) shows the waveforms of the whole system in transient state. V_{OUT} is 0.684V, V_{LX} 2.09V and V_{LXS} 1.90V. Difference between V_{LX} and V_{LXS} is 0.19V. In Fig. 14(b), waveforms in steady state are shown. V_{OUT} is 1.2V, V_{LX} 3.26V and V_{LXS} 3.05V. Difference between them is 0.21V, almost equal to that in Fig 14. (a) (transient state). It can be figured out that the time from V_{LX} reaching its highest point to S1 being turned on is almost equal in transient and steady state. Fig. 14 (c) shows the waveforms of the whole system in steady state with soft switching activated. V_{OUT} is 1.2V, V_{LX} 3.26V and V_{LXS} 3.26V. It can be seen that if “Soft Switching” is not activated, S1 will be turned on when V_{LX} moves to V_{LXD} , about 0.2V lower than its peak value V_{LXZ} . If soft switching activated, S1 is turned on exactly when V_{LX} reaches its highest point. In this example, $V_{LXZ}=3.26V$. This soft switching technique does work properly.

Fig. 13. Input and output waveform of “Peak Detector”

(a) Transient state

$V_{OUT}=0.684V$, $V_{LX}=2.09V$, $V_{LXS}=V_{LXD}=1.90V$

(b) Steady state
 $V_{OUT}=1.2V$, $V_{LXZ}=3.26V$, $V_{LXS}=V_{LXD}=3.05V$

(c) "Soft Switching" activated
 $V_{OUT}=1.2V$, $V_{LXZ}=3.26V$, $V_{LXS}=3.26V$

Fig. 14. Gating signal and V_{LX} waveforms

V. CONCLUSIONS

In this paper, a new soft-switching control technique for boundary-mode buck converters is presented. Operation principle is analyzed and integrated control circuit design is performed. The whole integrated circuit system is under fabrication. Hspice simulation results are shown to illustrate the effectiveness of the proposed control concept.

The designed integrated circuit controller with the

proposed control approach is able to compensate the circuit propagation delay and automatically track the optimum switching timing. The smart controller guarantees soft switching for boundary mode buck converters. Similar concepts apply well to boost and buck-boost converters. Power supply design will become simpler with this kind of smart IC controller.

REFERENCES

- [1] A. I. Pressman, *Switching Mode Power Supply Design*, 2nd ed., pp. 488-489, 1999.
- [2] Q. M. Li, F. C. Lee, M. M. Jovanovic, "Large-signal transient analysis of forward converter with active-clamp reset," *IEEE Trans. Power Electronics*, Vol.17, No.1, 2002.
- [3] S. Korotkov, V. Meleshin, A. Nemchinov, S. Fraidlin, "Small-signal modeling of soft-switched asymmetrical half-bridge DC/DC converter," *IEEE Applied Power Electronics Conference*, pp.5-9, 1995.
- [4] T. M. Chen, C. L. Chen, "Analysis and design of asymmetrical half bridge flyback converter," *IEE Proc.- Electric Power Applications*, Vol.149, No.6, pp.433-440, 2002.
- [5] Y. H. Leu, C. L. Chen, "Improved asymmetrical half-bridge converter using a tapped output inductor filter," *IEE Proc.- Electric Power Applications*, Vol.150, No.4, pp.417-424, 2003.
- [6] X. Wu, J. M. Zhang, Z. Qian, "Optimum design considerations for a high efficiency ZVS full bridge DC-DC converter," *INTELEC*, pp.338-344, 2004.
- [7] Y. Jang, M. M. Jovanovic, "A new family of full-bridge ZVS converters," *IEEE Trans. Power Electronics*, Vol.19, No.3, pp.701-708, 2004.
- [8] S. Y. Lin, C. L. Chen, "On the leading leg transition of phase-shifted ZVS-FB converters," *IEEE Trans. Industrial Electronics*, Vol.45, No.4, pp.677-679, 1998.
- [9] C. J. Tseng, C. L. Chen, "A passive lossless snubber cell for non-isolated PWM DC/DC converters," *IEEE Trans. Industrial Electronics*, Vol.45, No.4, pp.593-601, Aug. 1998.
- [10] Z. Yingqi, P. C. Sen, "A new soft switching technique for buck, boost and buck-boost converters," *IEEE Industry Application Society Meeting*, Vol.4, pp.13-18, 2002.