Threshold Voltage Start-up Boost Converter for Sub-mA Applications

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Abstract

A threshold voltage start-up (TVS) scheme for a boost converter is presented. The TVS converter could start up at the average threshold voltage of the fabrication process, and converts a fluctuating (energy harvesting) input of 0.2V to 0.9V to a regulated output of 1.2V. It operates in discontinuous conduction mode with peak current control (and thus operates with pulse frequency modulation) to reduce switching loss at light loads. The converter was designed with an AMS 0.35μm CMOS process and measured 675μm×615μm. The maximum efficiency is 83% at an output current of 1mA with an input voltage of 0.9V.

Keywords: Boost converter, DC-DC converter, energy harvesting, PFM, start up

1. Introduction

Energy harvesting can be employed in many applications, and one of the applications is the wireless micro-sensor network [1] that consists of several to thousands of distributed nodes which sense and process data and pass the results to end-users. This application is useful for military target tracking, industrial monitoring and home environmental control, to name a few. Since there are too many sensing nodes in the network, it is impossible to replace batteries for these nodes regularly, and energy harvesting techniques with energy storage components could theoretically provide them with an infinite lifetime.

Some researchers assume a voltage source of at least 1V is available for energy harvesting systems [2]~[4]. However, some sources such as solar cells vary dramatically with a 24-hour solar cycle for outdoor applications [5]. The power profile of a solar cell is fluctuating and is different from a regular battery. Therefore, a special converter (Figure 1) for converting this fluctuating source to a regulated voltage is needed.
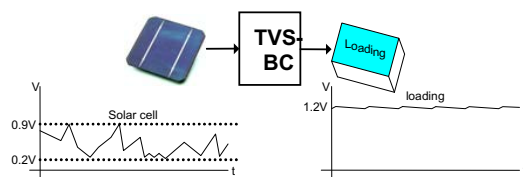

Figure 1: Operation of TVS boost converter

2. Start-up mechanisms

2.1 Comparison of start-up schemes

The start-up of a buck (step-down) switching converter poses no problem, as the functional blocks are driven by the input (or source) voltage V_s which is the highest voltage of the system. For a boost converter, in order to drive the output switch (usually a PMOS transistor) effectively, the buffer has to be driven by the highest voltage of the converter, which is the output voltage V_o. However, at start-up, V_o is zero and the buffer cannot even function. Therefore, special care has to be taken, but very few papers in the literature discussed the start-up circuitry for boost converters.
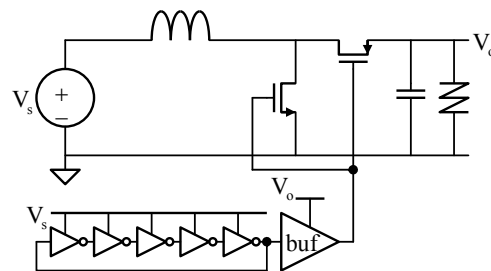

Figure 2: Conventional start-up scheme

One start-up mechanism of a boost converter was discussed in [6] (Fig. 2). It made use of a conventional ring oscillator with a conventional inverter driven by the supply voltage V_s. Therefore, the minimum start-up voltage $V_{st(min)}$ has to be higher than the threshold voltages of the employed process to turn on and off the power transistors effectively. In fact, the converter used a 0.6μm CMOS process with $V_{tn} = |V_{tp}| = V_{th(ave)} = 0.85V$, and $V_{st(min)}$ was demonstrated to be $1.18V_{tn} = 1V$. The ring oscillator

generates a 50% duty cycle clock for the switches, and ideally, the converter could reach $2V_s$ if the inductor current is in continuous conduction mode (CCM). However, due to a low load current, the inductor current would operate in discontinuous conduction mode (DCM), and also due to losses, with 1V for start-up, the unregulated output voltage thus achieved is $1.2V_{st(min)} = 1.2V$. In [6], the power stage was driven by the output voltage V_o directly to turn on the PMOS power transistor, and the output capacitor is charged to the input voltage prior to the start-up process. This charge up time is proportional to V_o, and is longer for a higher V_o. Note that the start-up circuit has to be disconnected from the control loop in the steady state, so as not to influence the proper control of the converter.
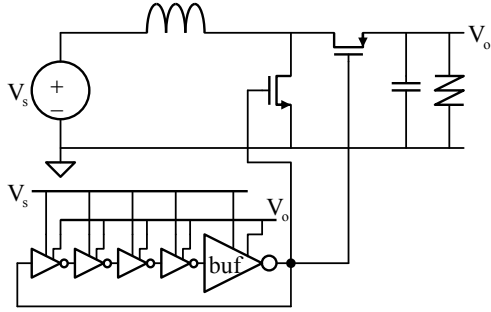

Figure 3: TVS start-up scheme

The proposed start-up scheme is shown in Fig. 3. It also uses a 5-stage ring oscillator to achieve spontaneous oscillation and generate the 50% duty cycle clock. However, the inverters and inverting buffer are driven by both the input supply voltage V_s and the output voltage of the converter V_o, called dual-supply inverter (NOT_D) as shown in Fig. 4.
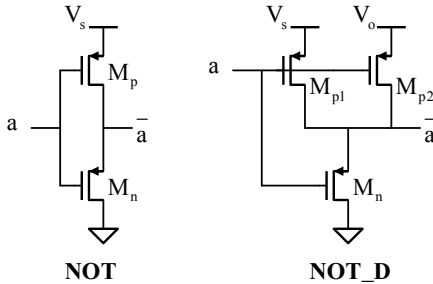

Fig. 4 Conventional and dual-supply inverter

For a conventional inverter NOT, the output swing is between V_s and Gnd. For the dual-supply inverter NOT_D, the output swing depends on the magnitudes of V_s and V_o. Assume the input to the inverter 'a' is low ('0') such that M_n is off, with r_{p1} and r_{p2} the on-resistance of M_{p1} and M_{p2} respectively, the high output voltage V_{oH} can be computed

$$\frac{V_2 - V_{oH}}{r_{p2}} = \frac{V_{oH} - V_1}{r_{p1}} \qquad (1)$$

$$V_{oH} = \frac{r_{p1}V_1 + r_{p2}V_2}{r_{p_1} + r_{p2}} \qquad (2)$$

Thus, V_{oH} is sandwiched between V_s and V_o. Next, assume $V_o > V_s$, the voltage swing of V_{out} of the ring oscillator is then between $(r_{p1}V_1+r_{p2}V_2)/(r_{p1}+r_{p2})$ and Gnd, which is higher than that of the conventional inverter. On using the dual-supply ring oscillator, the converter could be started up with the average threshold voltage $V_{th(ave)} = (V_{tn}+|V_{tp}|)/2$, and we denote this scheme as Threshold Voltage Start-up (TVS) scheme. The unregulated output voltage obtained is $1.85V_{th(ave)}$. The process we used is a 0.35μm process, with $V_{tn} = 0.59V$, $|V_{tp}| = 0.7V$. Hence, $V_{th(ave)}$ (and so is $V_{st(min)}$) = 0.65V. When the supply voltage V_s is equal to $V_{th(ave)}$, the start-up circuitry is activated and powered by both the input voltage V_s and the output voltage V_o. The built-in positive feedback mechanism helps boosting the output voltage up, such that $V_{th(ave)}$ is good enough for the start-up process. During start-up, V_o is unregulated, but when V_o reaches $1.85V_{th(ave)}$ = 1.2V, the control will be handed over to the steady state controller to regulate the output voltage to the desired value. The start-up circuitry is only 2% of the power transistors. The switching frequency of the ring oscillator is in the order of MHz. The results are summarized in Table 1.

Table 1: Conventional start-up scheme vs TVS scheme

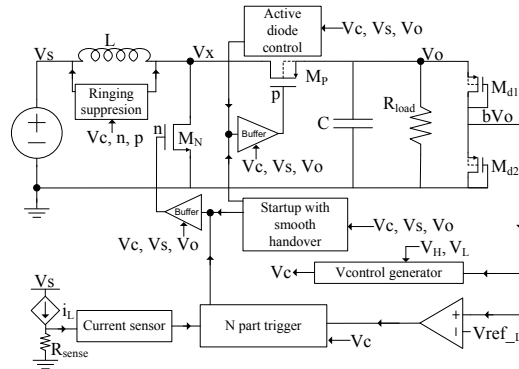|	Minimum start-up input voltage $V_{st(min)}$	V_o with $V_{st(min)}$ only
[6]	1.18 $V_{th(ave)}$	1.2 $V_{st(min)}$
TVS	$V_{th(ave)}$	1.85 $V_{st(min)}$

3. Control Scheme of TVS Boost Converter

Fig. 5 Block diagram TVS boost converter

The complete control scheme of the TVS boost converter is shown in Fig. 5 and the various operation modes of the converter are shown in Fig. 6. The start-up scenario, under light load and heavy load condition in the steady state with peak current control, and start-up after shutdown are all shown.
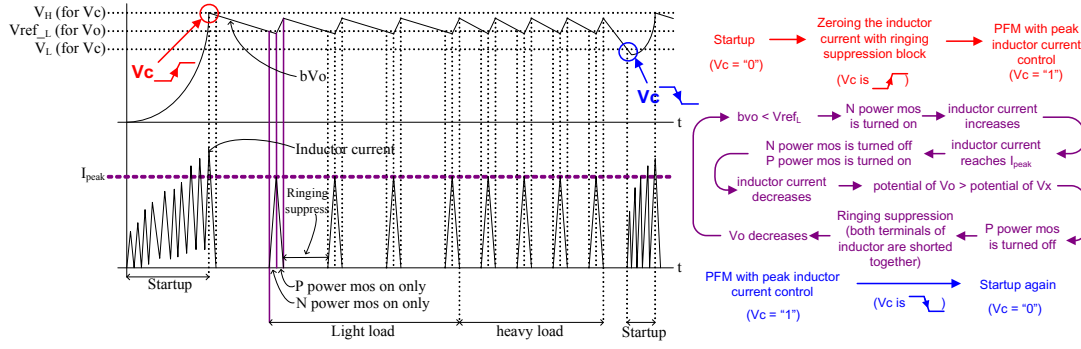
Fig. 6 Output voltage and inductor current of TVS under different operation modes

During start-up, V_o increases faster and faster, and when V_o reaches the high voltage limit V_H, the start-up process stops, and the V-control generator sets the control signal V_c = "1" and the converter enters the handover mode to avoid V_o from overshooting. After the short period of handover, the converter operates with peak current control in DCM, and as such, the switching frequency depends on the load, and the converter is considered to operate in PFM (pulse frequency mode) control.

The PFM controller can be separated into two parts. The power transistor M_N is controlled by the N Trigger, Current Sensor and Comparator, and the power transistor M_P is controlled by the Active Diode Control. When V_o drops and bV_o drops below V_{ref_L}, M_N is turned on and the inductor current I_L ramps up. When I_L reaches I_{peak}, M_N is turned off, and I_L charges up the V_x node and M_P is turned on by the Active Diode Control block, and I_L charges up V_o through M_P. The inductor current ramps down, and when it drops to zero, M_P is turned off by the Active Diode Control block. With both M_P and M_N are turned off, the converter then enters the free-wheeling mode. The ringing suppression transistors M_{ip} and M_{in} are turned on by the ringing suppression block until the next cycle begins.

Fig. 6 shows that when the load increases, the switching frequency of the converter also increases. If V_o drops below V_L suddenly, the converter changes from the PFM mode to the start-up mode directly to charge up V_o, followed by the handover process and eventually return to the PFM mode. As the converter operates in the PFM mode, a variant of band-band control, no compensation network is needed.

4. Circuit Implementation

Logic components: Logic circuits used in the TVS converter have to work in both start-up and PFM mode and are of dual-supply design. Each logic block is disabled with the control signal V_c differently so that they are powered up by V_o only after starting up.

V-control generator: It determines when the start-up process is finished and issues the signal V_c = "1" to shut off the start-up circuitry and puts the converter in the PFM control mode. To avoid glittering, a voltage hysteresis with a high and low threshold voltage is introduced.

Current sensor: It employs W/L ratio matching of M_N and uses a simple common gate amplifier with a constant bias current. A large peak inductor current causes a large conduction loss by M_N at the peak current and hurts the efficiency. Therefore, the best is to set the maximum peak inductor current such that at the minimum input voltage with the maximum load current, the converter is operating at the boundary between CCM and DCM. Finally, the peak inductor current is set to around 42mA.

Active diode control: The active diode is modified from [7]. It compares V_x and V_o using a common gate amplifier and turns off M_P to avoid reversion current.

Voltage divider: The minimum current of the converter is designed to be 100μA, and if the loss due to the resistor string is 1%, then the resistors have to be in the order of 1MΩ, which will take up too much silicon area. Here, we set b = 0.5 and we use two transistors in series to get the required voltage division. The output voltage V_o is designed to be 1.2V, which is smaller than $2\times|V_{tp}|$, hence the two PMOS transistors M_{d1} and M_{d2} are working in the sub-threshold region.

5. Measurement

To demonstrate the proposed start-up scheme, a test chip was fabricated using 0.35μm CMOS process, the performance of threshold voltage start-up and low voltage input are the same as the simulated results. However, the maximum efficiency is reduced by 3% comparing with the simulation, which may be due to the unexpected noise occurred in the inductor current that increases the true r.m.s. (root-mean-square) of the input current. The overall converter performance is summarized in Table 2.

Table 2: Chip performance summary

Technology	0.35μm CMOS process
Inductor / Capacitor	4.7μH / 500nF
Switching frequency	7MHz (startup) 700kHz – 15kHz (PFM)
Input supply voltage	0.15V – 0.9V
Output voltage	1.2V
Output ripple voltage	<24mV
Load current	0.1mA – 1mA
Efficiency	Max. 83%
Line regulation	12.4mV/V
Load regulation	19.8mV/mA

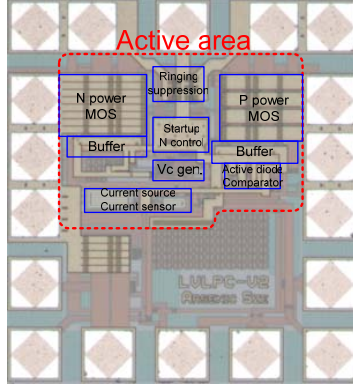**Fig. 7 Die photo of tested chip**

Fig. 7 shows the die photo of the TVS boost converter. It measures 675μm×615μm. Fig. 8 shows the start-up response of the converter with V_s = 0.65V, which is midway between V_{tn} and $|V_{tp}|$.
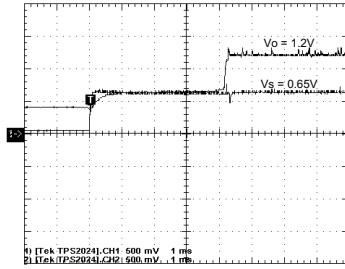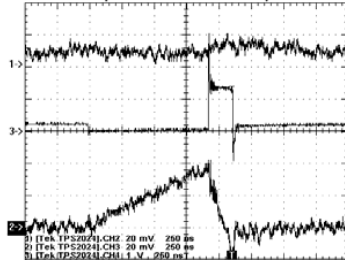

Fig. 8 Start-up response of TVS converter

Ch 1: V_o (AC coupling); Ch 2: Inductor current; Ch 3: V_x

Fig. 9 Min. supply voltage with max. loading current

Fig. 9 shows the steady state response of the converter with minimum supply voltage (0.2V) and maximum

current loading (1mA). The inductor current is too small to be measured by current probe and it is measured by the voltage drop across a 1Ω resistor in series using TPS 2024 instead. The converter is operating in good DCM mode as shown by the trace of V_x: when the inductor current is zero, V_x is equal to V_s rather than ringing.
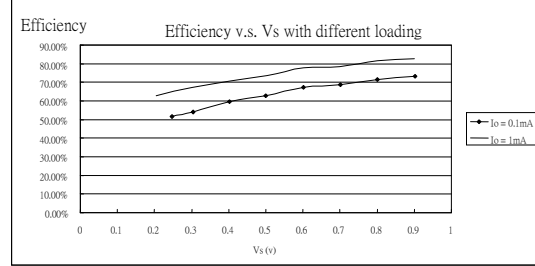

Fig. 10 Measured efficiency vs V_s and I_o

The converter operates in PFM, and when the input supply voltage is very low (200mV) and the load current is very high (1mA), the converter switches faster, and the maximum switching frequency occurs at the boundary of CCM and DCM. The highest and lowest switching frequency is 700kHz and 15kHz respectively. The maximum output ripple voltage is 24mV, which is 2% of V_o. The maximum efficiency is 83% (Fig. 10).

6. Conclusion

A boost converter that could start-up at the average threshold voltage is designed, fabricated and tested. It could operate at V_s from 0.2V to 0.9V. Moreover, the maximum efficiency is up to 83% at 1mA output current and 0.9V input voltage.

7. References

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