A self-start circuit with asymmetric inductors reconfigurable technology for dual-output boost converter for energy harvesting

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Abstract  A self-start circuit with asymmetric inductors reconfigurable technology for dual-output boost converter for energy harvesting is presented in this paper. It is found that the cross-coupled LC oscillator with asymmetric inductors can output much higher voltage than ordinary oscillators. Thus, the asymmetric inductors reconfigurable technology (AIRT) is used in the self-start circuit and a minimum startup voltage of 150mV is achieved. The AIRT realizes dual-output and improves the utilization of chip pins by reusing inductors in the self-start circuit and the boost system. The self-start circuit and the boost system are implemented in a 0.13μm CMOS process and a 73.7% converter efficiency is achieved. The chip area of the boost converter is 0.155mm². The area occupied by self-start circuit is only of 0.006mm² without other extra energy sources.

Keywords: boost converter, energy harvesting, self-starting, asymmetric inductors reconfigurable technology (AIRT)
Classification: Integrated circuits (memory, logic, analog, RF, sensor)

1. Introduction

With the development of the Internet of Things and wearable devices, the low supply voltage and low power requirements of these applications challenge the power management circuit design. The micro energy harvesting technology, as a reliable solution, can generate electrical energy from other energy sources like solar [1, 2, 3], thermal [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18], piezoelectric [19, 20, 21] and radio waves [22, 23, 24]. However, the voltage generated by thermoelectric generators (TEGs) or photovoltaic (PV) panels is only a few tens of millivolts or a few hundred millivolts, which is hard to drive general circuits. So, a boost converter is usually used in an energy harvesting system. The difficulties in designing the boost converter are how to start the converter and keep high output efficiency under an ultra-low input voltage. In previous research, external energy sources have been used to start the boost converter at low input voltages. Examples include external battery [25], MEMS switches [26], and auxiliary off-chip antenna [27]. Usually, it is difficult to integrate these additional energy sources into chips, which limits the application of the micro energy harvesting greatly. Thus, boost converters with high integration level and self-start ability attract great attention. The most popular self-start architecture is the combination of LC oscillator and charge pump, like [28]. However, the fly capacitors in charge pump usually occupy a large area. Moreover, the inactive inductors in the LC oscillator will waste chip pins after the boost converter starts.

To address the above problems, a self-start circuit with asymmetric inductors reconfigurable technology (AIRT) is proposed in this paper. It is found that the cross-coupled LC oscillator using asymmetric inductors could generate much higher output voltage than the input voltage. By adopting the AIRT, the self-start circuit starts the boost converter at 150mV with a small area. Meanwhile, the technology increases the utilization rate of the chip pins and achieves dual-output by reusing inductors.

2. AIRT self-start mechanism and AIRT self-start circuit

2.1 AIRT self-start mechanism

In our proposed self-start circuit, the key point is that the peak output voltages generated by the cross-coupled LC oscillator with asymmetric inductors are higher than that of traditional LC oscillator. The base architecture is shown in Fig. 1, where $C_{1,2}$ are parasitic capacitance of $M_{1,2}$ and diodes. The circuit inside the red dotted box is a cross-coupled oscillator. Unlike ordinary ones, $L_1$ and $L_2$ are given different inductance values. When the oscillator is stable, the smaller inductor will generate a higher peak voltage. And the ratio of $L_1$ and $L_2$ affects the peak values of output voltages ($V_{1,2}$) a lot. As shown in Fig. 2, when the input voltage is 150mV and the value of $L_1/L_2$ is 4, the peak output voltages of the circuit reach 0.37V and 0.88V. The voltages on $C_{1,2}$ and $C_{1,2}$ are 0V and 0.27V, respectively. Therefore, the asymmetric LC oscillator is considered to

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Fig. 1  Base architecture of the asymmetric cross-coupled LC oscillator.
replace the charge pump to startup the boost system.

References [29, 30] describe the working process of the current-limited ordinary LC oscillator. However, the working process of asymmetric LC oscillator has never been studied before. Here, the relationship between the inductance ratio and peak output voltage is analyzed according to the circuit simulation results.

Taking L1=L2 as an example, the stable oscillation waveforms of the circuit in Fig. 1 are shown in Fig. 3. For the convenience of analysis, the subthreshold effect is not considered. When M1 is on, L1 is charged. The current waveform of I_{L1} is a straight line. At this time, M2 is off, the energy on L2 exchanges between L2 and C2, the current waveform of I_{L2} is a sine curve. Therefore, for cross-coupled oscillators, when I_{L1} shows a sinusoidal trend, I_{L2} changes linearly. Similarly, when I_{L1} changes linearly, I_{L2} shows a sinusoidal trend.

For the sine curve part, the waveform is described as the following equation.

\[ I_s = I_{max1} \cdot \sin \left( \frac{2\pi}{T_1} \cdot t_{sa} \right) \] (1)

where \( I_{max1} \) is the peak current of I_{L1}, \( T_1 \) is the oscillation period when energy exchanges between L1 and C1, which equals \( 2\pi \sqrt{L_1C_1} \).

For line part, the waveform is described as the following formula

\[ I_s = \frac{V_n}{L_1} \cdot t_{sa} \] (2)

At the time of critical point between the straight line and the sine curve, (1) and (2) have the same value and derivative value. We have:

\[ \frac{d}{dt} \left[ I_{max1} \cdot \sin \left( \frac{2\pi}{T_1} \cdot t_{sa} \right) \right] = \frac{V_n}{L_1} \] (3)

\[ \frac{V_n}{L_1} \cdot t_{1b} = I_{max1} \cdot \sin \left( \frac{2\pi}{T_1} \cdot t_{1a} \right) \] (4)

\( t_{1a} \) and \( t_{1b} \) are marked in the Fig. 3.

(3) can be rewritten as

\[ t_{1a} = \frac{T_1}{2\pi} \cdot \cos^{-1} \left[ \frac{V_n}{L_1 \cdot I_{max1}} \cdot \frac{T_1}{2\pi} \right] \] (5)

From Fig. 3, it can be obtained

\[ t_{1b} = \frac{T_2}{2} - t_{2a} = \frac{T_2}{2} - \frac{T_1}{2\pi} \cdot \cos^{-1} \left[ \frac{V_n}{L_2 \cdot I_{max2}} \cdot \frac{T_1}{2\pi} \right] \] (6)

where \( I_{max2} \) is the peak current of I_{L2}, \( T_2 \) is the oscillation period when energy exchanges between L2 and C2, which equals \( 2\pi \sqrt{L_2C_2} \). Substituting (5)(6) into (4). Thus,

\[ \frac{V_n}{L_1} \cdot \left[ T_2 \right] - \frac{T_2}{2\pi} \cdot \cos^{-1} \left( \frac{V_n}{L_2 \cdot I_{max2}} \cdot \frac{T_1}{2\pi} \right) = I_{max1} \sqrt{1 - \left( \frac{V_n}{L_1 \cdot I_{max1}} \cdot \frac{T_1}{2\pi} \right)^2} \] (7)

Similarly, the equation (8) for L2 is obtained.

\[ \frac{V_n}{L_2} \cdot \left[ T_2 \right] - \frac{T_2}{2\pi} \cdot \cos^{-1} \left( \frac{V_n}{L_1 \cdot I_{max1}} \cdot \frac{T_1}{2\pi} \right) = I_{max2} \sqrt{1 - \left( \frac{V_n}{L_2 \cdot I_{max2}} \cdot \frac{T_1}{2\pi} \right)^2} \] (8)

According to the law of conservation of energy, the energy in the inductors will be completely transferred to the capacitors and we have

\[ \frac{1}{2} L_1 (I_{max1})^2 = \frac{1}{2} C_1 (V_{peak1} - V_n)^2 \] (9)

\[ \frac{1}{2} L_2 (I_{max2})^2 = \frac{1}{2} C_2 (V_{peak2} - V_n)^2 \] (10)

where \( V_{peak1} \) and \( V_{peak2} \) are peak voltages of \( V_1 \) and \( V_2 \). According (7)(8)(9)(10), once L_{1,2} and C_{1,2} are determined, the values of \( V_{peak1} \) and \( V_{peak2} \) are determined accordingly.

To obtain the relationship between the value of (L_{1,2}) and \( V_{peak1,2} \), MATLAB is used to solve the equations. And the results are shown in Fig. 4.

The points in Fig. 4 represent the actual simulation data, and the green line and blue line are the fitting curves obtained in MATLAB according to the (7)(8)(9)(10). It can be seen from Fig. 4 that the actual simulation data are distributed according to the curves.

### 2.2 AIRT model and self-start circuit

The cross-coupled LC oscillator with asymmetric inductors occupies two pins for external inductors. It is extravagant if the inductors are inactive after the boost converter starts. To improve the utilization rate of chip pins, the inductors
reconfigured in the oscillator mode and the boost converter mode. The circuit model of the AIRT is shown in Fig. 5(a) and Fig. 5(b), where $M_{1,2}$ are low $V_{th}$ transistors, $C_{1,2}$ are parasitic capacitance of $M_{1,4}$, and $S_{1,4}$ are ideal switches. When $S_{1,2}$ are on, $S_{3,4}$ are off. $L_{1,2}$ and $M_{1,2}$ constitute a basic LC oscillator, as shown in Fig. 5(a). $V_{o1}$ and $V_{o2}$ will rise, which have been analyzed in section 2.1. When the $V_{o2}$ is high enough, $S_{1,2}$ are turned off and $S_{3,4}$ are turned on. $L_{1,2}$ and $M_{3,4}$ constitute two basic boost structures, as shown in Fig. 5(b). The AIRT circuit reconfigures $L_{1,2}$ in the oscillator and boost converters.

The self-start circuit consists of the AIRT circuit shown in Fig. 5(c) and Power on Reset circuit (POR) shown in Fig. 5(d), where $M_{5,8}$ are used as switches. When the input voltage is coming, the POR circuit outputs ‘0’. $M_{7,8}$ are off. $M_{1,2}$ are turned off. At this time, $L_{1,2}$ and $M_{3,4}$ constitute an LC oscillator. The output voltage of the oscillator starts to charge the $C_{L1,2}$. When the LC oscillator raises the voltage of $C_{L}$ to the POR threshold voltage, POR output ‘1’. $M_{7,8}$ are off. $M_{1,2}$ are turned off. At this time, $L_{1,2}$ and $M_{3,4}$ constitute the base boost structures. An ultra-low static current power on reset circuit is used to switch $M_{5,8}$. The POR circuit is nearly zero qiescent power to improve the circuit efficiency and reduce unnecessary power consumption.

### 3. Proposed architecture and behavior analyses

The proposed boost converter architecture is shown in Fig. 6. The power supply devices like TEGs are represented with a voltage source $V_{BV}$ and an internal resistor $R_{BV}$.

The proposed boost architecture consists of the PWM control module and the self-start circuit. And the transient behavior analyses of the architecture are as follows. 1) First stage. At the beginning of startup, $V_{out2}$ is low, POR1 outputs zero potential. The PWM control module is off. $N_{3,4}$ and $P_{3,4}$ constitute an asymmetric cross-coupled LC oscillator. $V_{out2}$ will rise according to the analysis in section 2. 2) Second stage. When the $V_{out2}$ is high enough, POR1 outputs a high voltage. The asymmetric cross-coupled LC oscillator is turned off. The PWM control module is on. $N_{2,3}$ and $P_{2,3}$ are controlled by the PWM signal. $V_{out2}$ rises to a set value. 3) Third stage. Once $V_{out2}$ has reached the set value, the output of POR2 turns to low. $P_{6}$ is on. $V_{out2}$ begins to supply the external load $R_{6}$ and the left branch converter. Finally, $N_{1,2}$ and $P_{1,2}$ are controlled by a PWM signal and $V_{out1,2}$ will rise to stable values.

### 4. Simulation results

According to the reference [11, 18], a suitable startup voltage $V_{BV}$ 150mV and $R_{BV}$ 5Ω are chosen. Fig. 7 illustrates the post-layout simulated waveforms of the proposed circuit. The working process of the system can be divided into three stages. First, the asymmetric cross-coupled LC oscillator starts working and the peak output voltage is rectified by the parasitic diode of $P_{2}$. Second, when the $V_{out2}$ rises to about 0.7V, the POR1 turns off the LC oscillator. The right branch converter enters the normal boost converter mode. Third, when the $V_{out2}$ is high enough (around 1V), POR2 turns on.
Fig. 7: Post-layout simulated waveforms of the proposed boost converter when the $V_{BV}$ is 150mV and $R_{BV}$ is 5Ω.

Fig. 8: Simulation results of minimum startup voltages over the different temperatures and process corners.

$P_6$, the right branch converter supplies the left branch converter and external load $R_6$. Finally, the left branch converter and right branch converter enter the normal working mode and output 0.8V/1.2V respectively. The simulation wave proves the analysis of the boost architecture in section 3.

Fig. 8 shows the simulation results of minimum startup voltages of the boost system over the different temperatures and process corners. The value of $L_1/L_2$ is 10. The worst-case startup voltage is 0.2V at $-20^\circ$C under slow-slow (ss) corners. The best-case startup voltage is 0.12V at 27°C under fast-fast (ff) corners. The minimum input voltage of this startup circuit is limited by three factors. The first one is that the pMOS transistors used as switches are not equal to the metal wire or ideal switches. A $V_{GS}$ is needed to turn on pMOS. The second one is the initial output voltage of the POR1 circuit is not zero potential. In the initial process of circuit startup, the output voltage of the POR1 circuit will rise slightly with the rise of $V_{out2}$, and the simulation result is about 30mV. As a result, the voltage at the gate of $P_3,4$ is not zero voltage level, which raises the startup voltage. The third one is a voltage loss of the parasitic diode of $P_{1,2}$. To make the PWM module work normally, its operating voltage is at least about 400mV. The voltage loss of the parasitic transistor of $P_2$ is about 600mV, and the peak output voltage of the oscillator should be about 1V. When the $L_1/L_2$ ratio is 10, the input voltage is around 100mV according to Fig. 4.

Fig. 9 shows the simulated efficiency versus the energy harvesting device input voltage $V_{BV}$. The total efficiency of the proposed boost converter is 73.7% at 150mV.

Fig. 10 shows the layout of the boost converter implemented in a 0.13μm CMOS process. The chip has a core
active area of 0.155mm², and the area of the self-start circuit is 0.0060mm² including N₃, μP₄, and POR1.

The devices parameters have been listed in Table I. Table II compares this work with other advanced low startup voltage boost converters in the analog and digital fields. It can be seen that the proposed converter achieved the smallest startup circuit area, lower input voltage, and higher efficiency. By using AIRT, the proposed converter achieves dual-output.

5. Conclusion

A self-start circuit for dual-output boost converter for energy harvesting is proposed in this paper. By using asymmetric inductors reconfigurable technology, the minimum startup voltage of 150mV is achieved. The ART not only realizes the low-voltage startup but also reuses inductors in LC oscillator and boost converter, which improves the utilization rate of chip pins. The self-start circuit and the converter are implemented in a 0.13μm CMOS process and a 73.7% converter efficiency is achieved. The chip area of the boost converter is 0.155mm². The self-start circuit occupies only an area of 0.006mm² without other extra energy sources.

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