Application Note

Ultra-low Voltage (150 mV) Start-up Design Based on TPS61299

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ABSTRACT

Water heaters are commonly used in daily life, the mechanism of which is similar to gas stoves. When ignition switch is triggered, fire is lit and the thermocouple is heated by the flame. At this time, a thermoelectric potential is generated, which in return will start the control system of the whole water heater, such as MCU. Therefore, the low voltage start up feature is preferred, cutting down the cost of selecting a thermocouple and the start-up time. Based on aforementioned application, an ultra-low voltage start-up scheme using BOOST converter TPS61299 is proposed in this application note.

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1 Introduction of Water Heater

In some energy harvesting applications, the voltage of the input source as low as 150 mV, thus a boost is needed to regulate a higher voltage for the system. Water heater is just a good example: When the water heater is switched on, piezo ceramic fires, a small fire occurs to raise the temperature of the thermocouple, this time due to the temperature difference at both terminals. The thermocouple begins to generate a thermal potential (as low as 150 mV) , acting as the input to the boost converter, which regulates the output to 3.3 V to turn on the control portion of the water heater, as is shown in Figure 1-1. However, it is hard for a boost to start up within a ultra low input voltage and the UVLO of most boost device is 1.8 V or 0.7 V. let along 150 mV. This application note provides a solution using TPS61299 to support the 150 mV ultra low input voltage system.

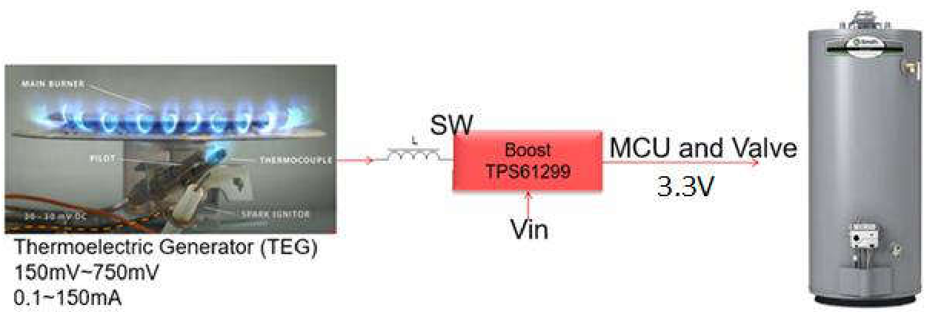

Figure 1-1. Water Heater Control Diagram

2 Low Voltage Start-up Boost Converter Introduction

2.1 General Introduction About TPS61299

The TPS61299 is a synchronous boost converter that operates with a hysteretic control scheme and can achieve ultra-low voltage start-up when the power input signal is only 150 mV when VIN>0.7 V. In addition, the TPS61299 consumes only 95 nA of quiescent current for high efficiency at light loads and the family products offers a wide input current limit from 5 mA to 1.9 A and supports optional true shutdown or force-through when EN is low. The TPS61299 provides fast transient performance modes and accurate load regulation modes for different systems.

2.2 Introduction about Traditional Start-up Process

Figure 2-1shows the traditional start up solution when power input (PVIN) and analog input (PVIN) are connected . Figure 2-2shows the Ultra power vin start up solution where PVIN and AVIN are powered separately. The internal start up process of the boost converter are the same.

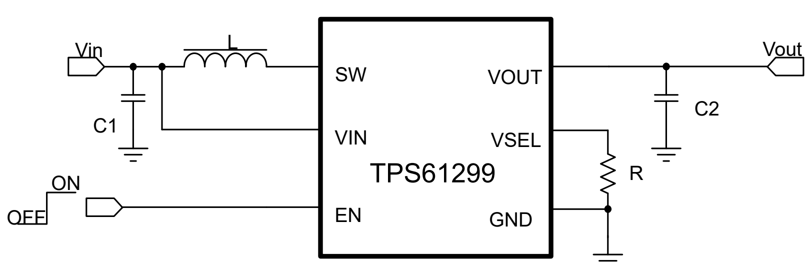

Figure 2-1. Typical Schematic of Traditional Start-up Design

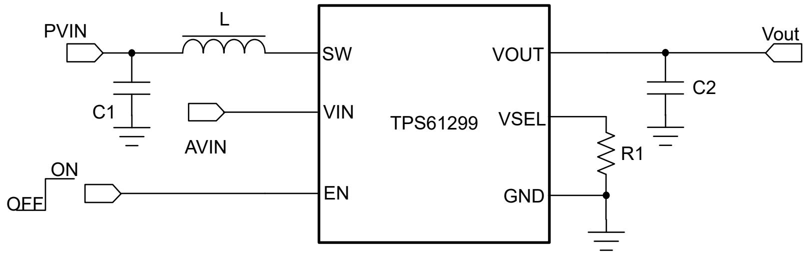

Figure 2-2. Typical Schematic With Ultra Low Input Voltage Start-up Design

After the EN pin is tied to high voltage, the TPS61299 begins to startup, the process can be divided into 5 stages, as is shown in Figure 2-3.

Stage 1: When output voltage is lower than 0.5 V, device behavior is the same as short protection, to limits the output power for the short protection.

Stage 2: As output voltage is higher than 0.5 V, the device operates at the boundary of Discontinuous Conduction Mode (DCM) and Continuous Conduction Mode (CCM), and the inductor peak current is limited to around 350 mA during this stage.

Stage 3: After the output voltage reaches 1.8 V, the TPS61299 starts to detect the output voltage configuration from VSEL pins, then latches the configuration. The version detection time depends on the resistance at VSEL pin, the higher resistance, the longer version detection time. For example, for 5 V normal version, the TPS61299 needs about 170 us for version detection. The TPS61299 checks the VSEL pin by reducing the resistor setting option to a higher setting option until the user finds the setting configuration with a 10-µs clock.

Stage 4: After detecting the configuration, the TPS61299 begin to latch the reference output voltage and the VOUT begins ramping to the target. The TPS61299 does not sense the VSEL pin during operation, so changing the resistor during operation will not change the VSEL setting. Toggling the EN pin during operation is one way to refresh it.

Stage 5: After version detection, TPS61299 continues switching and output ramps up further. For the high input current limit version devices, such as 250 mA, 500 mA, 1.2 A and 1.9 A version, TPS61299 reduces the inrush current during start-up by limiting the inductor average current lower than 500 mA (input current limit to 250 mA for 250 mA version), when output voltage is lower than 2.5 V. For When output voltage ramped over 2.5 V the aforementioned input current limit is released and set to version definition level.

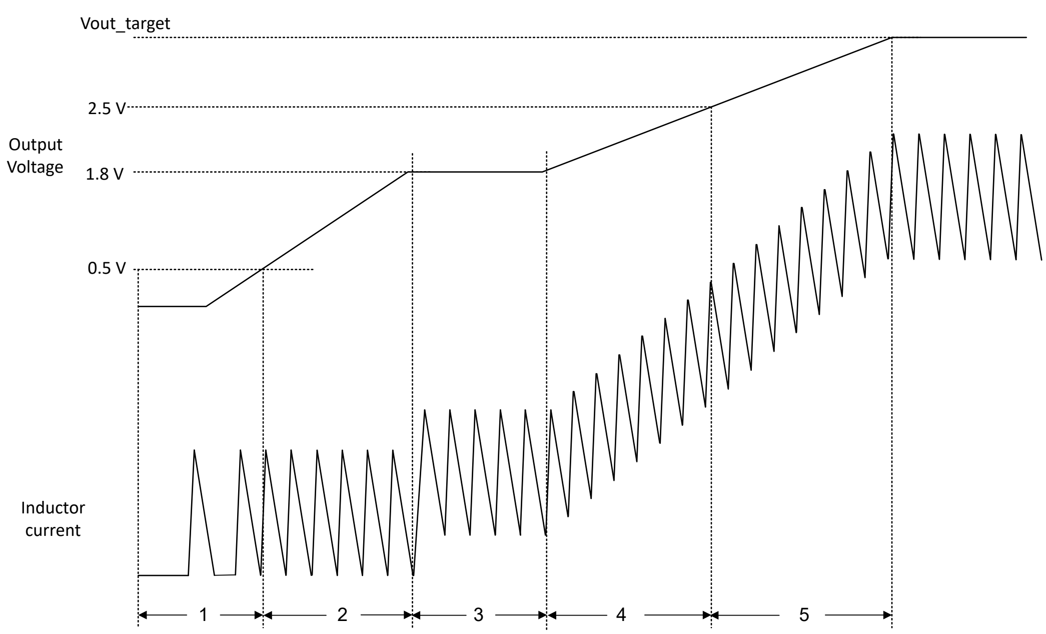

Figure 2-3. Start-up Process of TPS61299

2.3 Down Mode and Boost Mode Operation

To be added , during startup when the input voltage is higher than the output voltage, the TPS61299X works in down mode to maintain the switching state. In down mode, the high side PMOS source is switched to SW node, other than Vout (in boost mode) node. Refer to Figure 2-4 and Figure 2-6 to compare the difference of high side PMOS between down mode and boost mode. During the t_{off} period, the gate bus of the high side PMOS is pulled to the input voltage (AVIN) instead of ground, then the source node, that is SW node , can be charged to AVIN+V_{gs_th} due to the internal C_{gs} of the PMOS (V_{gs_th} is about 0.7V for high side PMOS), referring Figure 2-5to see the inductor current and SW node voltage. Therefore, the SW bus voltage is 0.7V higher than Vin, then the inductor can be discharged and the energy can be converted to the output.

During down mode, the high side PMOS works under saturation zone, other than fully turning on state , thus the efficiency is much lower than boost mode. In this way, the voltage drop across the PMOS is increased enough to regulate the output voltage. Under this mode, the power loss will also increase, and heat dissipation needs to be considered. Therefore, the current limit of the device version can be taken into account carefully because if the load is so heavy that the input current is close to the current limit, with the efficiency drop under down mode, the device can fail to start up normally. Also the current limit will decrease as well under down mode operation.

The device enters boost mode After the Vout ramps over input voltage. The source node of the high side PMOS is switched to VOUT bus, as is shown in Figure 2-6. Figure 2-7 shows the inductor current and SW node voltage waveforms. During the t_{off} period, SW high side PMOS is on, thus SW voltage is equal to VOUT, which means the drop voltage on the inductor is VOUT-VIN.

Overall speaking, the main difference between the start up solution as shown in are the difference of actual voltage at the VIN pin seen by the device, which determines the threshold when the device exits down mode and enters boost mode. Because the efficiency of boost mode is much higher than down mode, the behavior of start-up process may differ a lot, which will be discussed in more detail in Section 3.

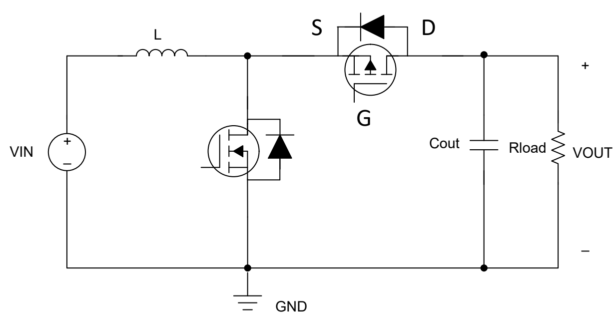

Figure 2-4. Down Mode Topology

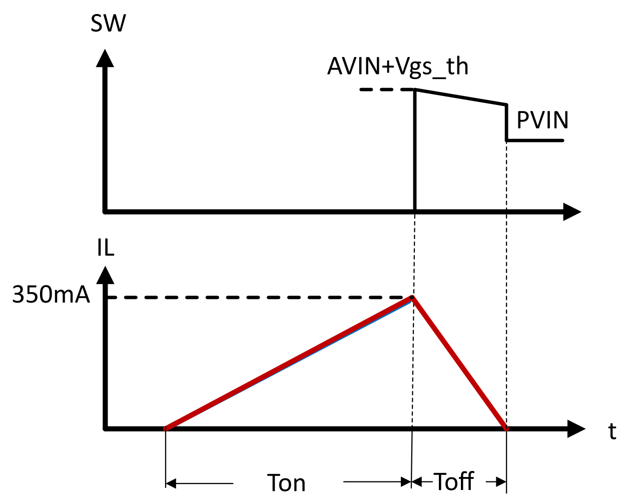

Figure 2-5. Down Mode Waveform

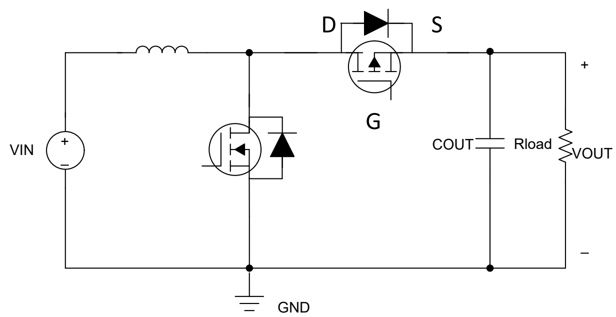

Figure 2-6. Boost Mode Topology

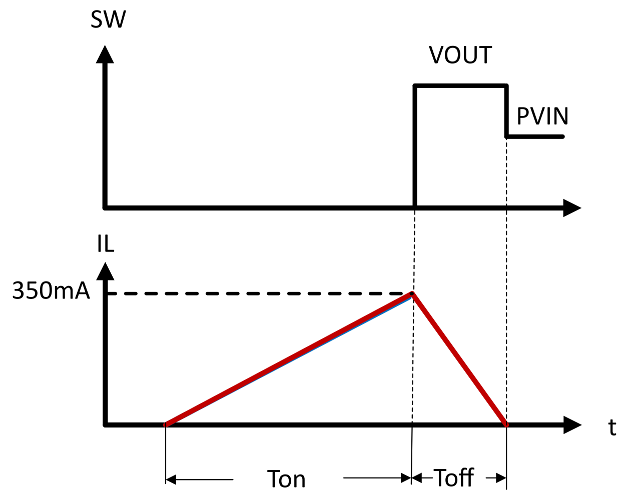

Figure 2-7. Boost Mode Waveform

3 TPS61299 Ultra-low Voltage Start-up Design

3.1 Ultra Low Voltage Start-up Set up

Figure 2-2 shows the process to realize 150 mV low-voltage start-up based on TPS61299-103 EVM, where AVIN and PVIN are separated. The relative parameters are stated in Table 3-1.

Table 3-1. Parameters Set-up

Parameters	Values
PVIN (SW)	150 mV
AVIN (VIN)	0.7 V
VOUT	3.3 V
L	1 uH
LOAD	OPEN

The start up progress is shown in Figure 3-1.

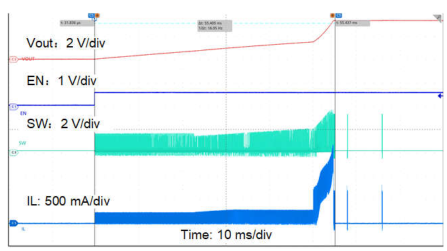

Figure 3-1. TPS61299 150 mV Input Voltage Start-up

In the following sections, elements such as AVIN, VOUT, and L are studied about how they influence the start up process.

3.2 The Way AVIN influence Start-up Process

Table 3-2 shows the start-up time △T varies with different AVIN, with VOUT =3.3 V, PVIN = 150 mV and L =1 uH. △T is the time when VOUT ramps from 10% to 90% of the target voltage. With the increase of AVIN, the startup time is reduced gradually.

Table 3-2. Start-up Time for Different AVIN

AVIN (V)	△T(ms)
0.7	55.4
1	81.6
1.2	88.6
1.5	92.8
2	96.1
3	244

Figure 3-2 and Figure 3-3 shows the start-up process with AVIN=0.7 V and 2 V ,with PVIN= 150 mV, VOUT=3.3 V, L=1uH. As is seen, the start-up process is faster with AVIN = 0.7 V. The start-up time varies under the two set-ups is mainly because the Down Mode period. The difference resulting from various AVIN is because the internal block should detect the AVIN and compare it with Vout to decide whether to exit down mode or enter Boost mode.

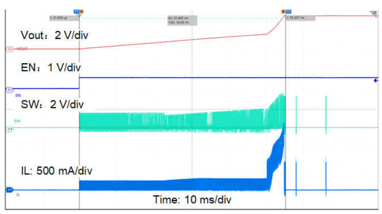

Figure 3-2. Start-up Waveform with AVIN = 0.7 V

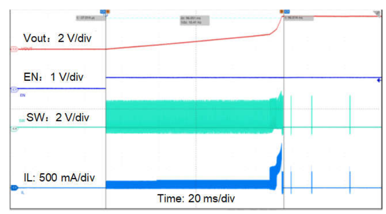

Figure 3-3. Start-up Waveform with AVIN = 2 V

In the initial stage as shown in Figure 2-3, when Vin is higher than Vout, the TPS61299 enters Down Mode, which schematic can been seen in Figure 2-4. Afterwords, the device exits down mode and enters BOOST Mode until VOUT ramps to AVIN. The lower AVIN is , the earlier the device exits down mode operation and enters boost operation. While under boost mode the efficiency is much higher because the high side MOSFET fully turns on other than works in saturation area, which means more energy can be converted to output thus the converter could regulate to target VOUT sooner.

Under down mode, during the T_{on} period, the Low side MOSFET turns on and the inductor current ramps up; during the T_{off} period, the Low side MOSFET turns off and High side MOSFET turns on in turn. According to the volt-second balance principle of inductor, the differentiation of inductor in Equation 1 and Equation 2:

During T_{on} period:

$$L\frac{di}{dt} = PVIN \quad (1)$$

During the T_{off} period:

$$L\frac{di}{dt} = SW - PVIN \quad (2)$$

The T_{on} period is much the same under the two cases because the PVIN is both 150 mV. While during T_{off} period, the voltage drop across inductor varies since the SW node voltage differs under different AVIN. The SW node voltage varies for that the source node of high side PMOS is charged to $AVIN+V_{gs(th)}$, as a result of PMOS internal C_{gs}. Figure 3-4 shows the inductor current with AVIN=2 V and 0.7 V , the off time is much longer with AVIN=0.7V.

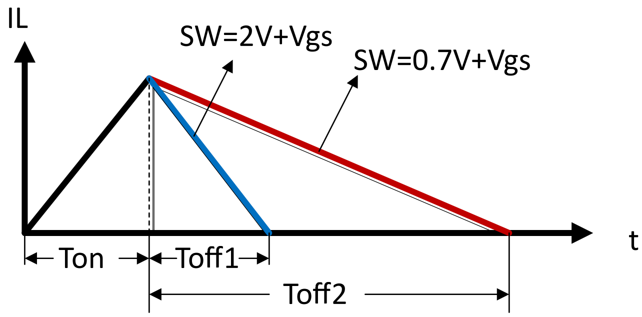

Figure 3-4. Inductor Current with Different AVIN

In summary, the recommendation is to choose lower AVIN to achieve ultra low VIN start-up. However, AVIN must be higher than UVLO of TPS61299, which means the minimum AVIN is 0.7 V.

3.3 The Way Vout Influence Start-up Process

This paragraph focuses on effects of Vout regarding with the lowest PVIN start-up. The Table 3-3 shows minimum PVIN supporting for regular start-up , under the condition that AVIN =0.7 V , L=1 uH the same, and target VOUT varies from each other.

Table 3-3. Minimum Start-up PVIN for Different VOUT

VOUT (V)	$PVIN_{min}$(mV)
1.8	90
3.3	120
5	140

As is shown inTable 3-3, the larger the VOUT is , the lower the PVIN startup can be achieved. The inductor current with different VOUT is shown in Figure 3-5. When VOUT is larger than AVIN, the device works under Boost mode. With PVIN no much difference, the main difference lie in the period when high side PMOS turns on, denoted as T_{off}.

As is shown, the lower Vout is , the more flat the inductor current ramp down, the longer T_{off} time is, which means more energy is converted to the output side during one switching cycle, because using the Toff period:

$$L\frac{di}{dt} = VOUT - PVIN \quad (3)$$

Thus the power converted to the output bus can be sorted from largest to smallest : VOUT=1.8V, VOUT=3.3V, VOUT=5V.

In conclusion, lower VOUT can achieve better and faster start up behavior.

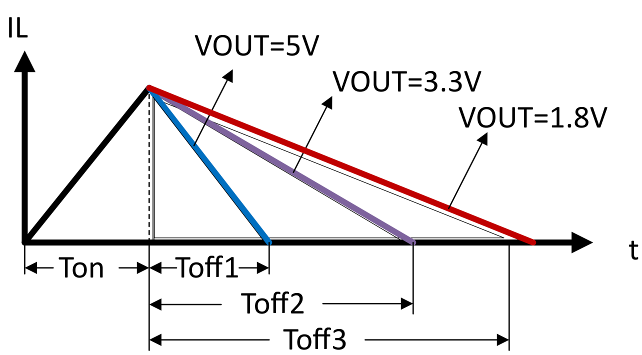

Figure 3-5. Inductor Current for Different VOUT

3.4 The Way L Influence Start-up process

Based on common sense, the lower power inductance may lead to more energy converting to the output side, regardless of the ripple and loop stability. However it is not all this case when DCR is taken into consideration, because larger DCR might lead to failure of starting up. This is a little different with how AVIN and VOUT influence start-up process, which is explained in detail.

Table 3-4shows the inductance and minimum PVIN which can achieve successful start-up, under the condition that VOUT=3.3 V, AVIN=0.7 V.

Table 3-4. Minimum PVIN for start-up VS Inductance

L(uH)	$PVIN_{min}$ (mV)
0.47	100
1	90
1.5	80
2.2	80
3.3	80
4.7	80
6.8	110
22	Fail to start up

Note

The inductance DCR selected in the experiments is controlled within 40 mΩ, and the experimental influence caused by the difference in Rdc is reduced as much as possible.

As is shown in Table 3-4, when inductance is smaller than 4.7 uH, with the increasing of inductance, the TPS61299 can achieve lower PVIN start up. However, when inductance is higher than 4.7 uH, continuing to increase inductance does not achieve a lower PVIN startup as expected. The reason why Startup fails to output normally should be related to the total energy of the inductor during excitation and discharge, so the reasons for this is further analyzed in Section 3.4.1.

3.4.1 Why With the Larger Inductance, The Smaller PVIN Start-up Can Be Achieved?

With inductance decreasing, the power converting to the output side is increased due to the smaller slope of inductor current , as is shown in Figure 3-6.

Therefore, according to the Equation 3, under the condition that $t_{on} < t_{on\_max}$, AVIN and VOUT are the same, the larger L is, the smaller di/dt is. Then the more energy can be stored during the t_{on} period and the more energy will be converted to the output during the t_{off} period. Therefore, with larger the inductance, lower PVIN startup can be achieved.

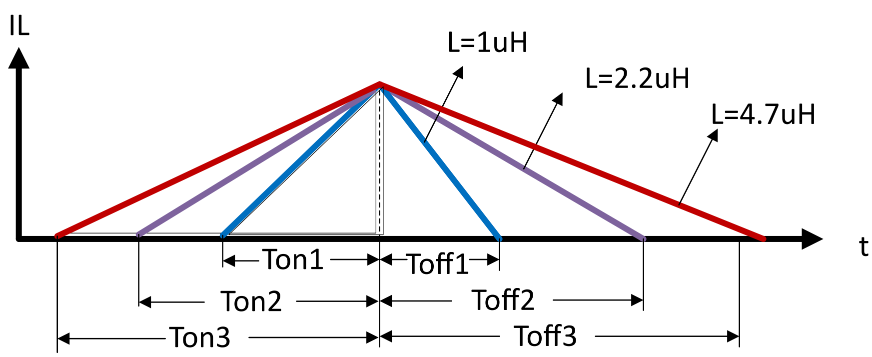

Figure 3-6. Inductor Current With Different L

3.4.2 Why Does The Inductance Continue to Increase, The Minimum PVIN to Start Up Is Not Lower

The T_{on_max} of the low side MOSFET limits the excitation time of the inductor, so after inductance exceeds a certain value, VOUT remains unchanged when the excitation time remains unchanged. The larger L is, the smaller the di/dt is. When the on time of low side MOSFET reaches T_{on_max} , peak current of the inductor hasn't reached hysteresis current (350 mA) , then the low side MOSFET is forced to turn off, after which the high side MOSFET turns on. Therefore less energy is converted , so VOUT cannot be regulated to target voltage normally.

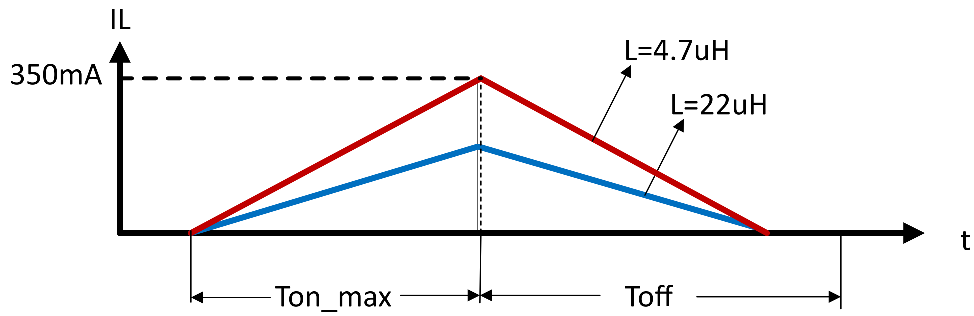

Figure 3-7. Inductor Current With Larger Inductance

3.4.3 Why 80 mV Can Start Normally While 70 mV Fail to?

Figure 3-8 and Figure 3-9 are the test waveforms when L=2.2 uH, AVIN=0.7 V, VOUT Target =3.3 V, and PVIN are 70 mV and 80 mV respectively. Figure 3-8, shows that PVIN=70 mV, and the output has not been raised to the target voltage.

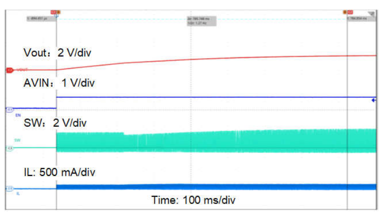

Figure 3-8. PVIN=70 mV (VOUT=2.0 V, Fail to Start up)

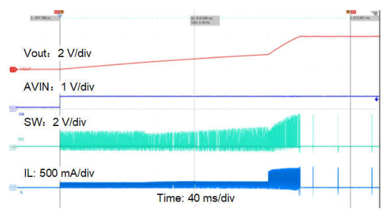

Figure 3-9. PVIN=80 mV (VOUT=3.3 V)

Inductor current under different PVIN are shown in Figure 3-10. When PVIN is only 70 mV, the input power signal is already quite weak, so when T_{on_max} is reached, the electric energy stored in the T_{on} stage is only enough to raise the output to 2.0 V, as is shown in Figure 3-10. When PVIN=80 mV, the power input is also relatively weak, But it can ensure that before T_{on_max}, the device can ensure that the electric energy storage is enough to raise the output to 3.3 V.

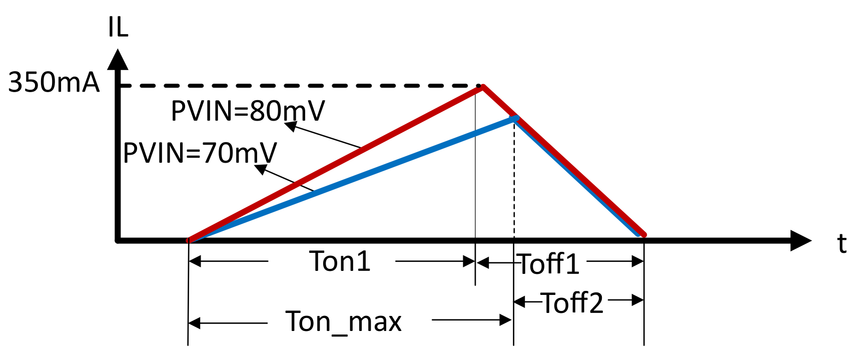

Figure 3-10. Inductor Current Curves for Different PVIN

4 Ultra-low Voltage Start-up Design

4.1 Test Waveform

According to the experimental test and analysis in the Section 3, , it's recommended to choose lower AVIN, lower VOUT and higher inductance, to achieve ultra low VIN start-up. However, AVIN should be higher than UVLO, which means the minimum AVIN is 0.7 V. To keep the t_{on} from reaching t_{on_max} , inductance of 1.5 uH or 2 uH is recommended. Considering all the above analysis, a typical solution is proposed to achieve extremely low voltage startup, as is shown in Table 4-1. The corresponding schematic is shown in Figure 2-2. The specific solution reference design is as follows:

Table 4-1. Design Parameters

PARAMETERS	VALUES
PVIN (SW)	80 mV
AVIN (VIN)	0.7 V
VOUT	3.3 V
L	1.5 uH or 2.2 uH
R1	0 Ω
C1	10 uF
C2	10 uF
LOAD	OPEN

The start up process is shown in Figure 4-1.

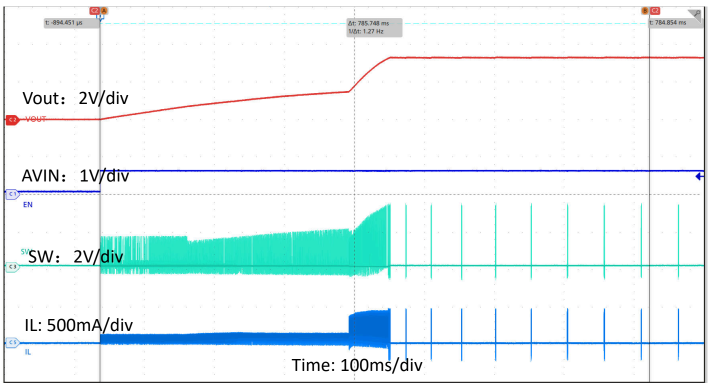

Figure 4-1. 80 mV PVIN Start-up Waveform

In conclusion, an ultra low-power input solution using BOOST converter TPS61299 is proposed and verified in this paper. And to optimize the start-up process, elements such as AVIN, VOUT and L are studied about how they influence the start-up. Finally, considering the practical inductance, and expected VOUT, a optimized solution with lower PVIN application is recommended and verified.

5 Summary

The Texas Instruments low-voltage start up feature allows for users to achieve minimum power Vin, which can achieve low-voltage battery startup or potential generated by thermo signal. In this process, the inductor can be lower than traditional start up design, which saves the total design size and cost. The low-input voltage start up feature is widely used in water heater, gas cooker, and so on.

6 References

1. Texas Instrument, *TPS61299 95 nA Quiescent Current, 5.5V Boost Converter with Input Current Limit and Fast Transient Performance* data sheet.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265