Application Note

A Long-Lifetime, Cost-Competitive Solution in Smart Meters Based on the TPS61094

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ABSTRACT

Smart meters, including gas and water meters, need to record information such as gas or water consumption and then communicate this information with a data center or end-customer. Smart meters are powered by the primary battery and need to support operation for 10 years or more. Most of the operation time is light load (about 20 uA), but during the data transmission, the load is a high pulse current load (about 250 mA). A common smart meter design challenge is supporting both high power consumption for data transmission and a long working lifetime. Some customers choose a lithium thionyl chloride ($LiSOCl_2$) battery to power the system because of low self-leakage current and high-power density(long lifetime). However, the $LiSOCl_2$ can't support high pulse current. The traditional solution is to use a $LiSOCl_2$ battery with a hybrid layer capacitor (HLC) package and use the HLC to support the high pulse current. But the HLC cannot control the $LiSOCl_2$ battery's discharge current and prevents the battery from operating at maximum capacity. Because of the HLC's poor performance at lower temperatures, customers must choose a larger and more expensive HLC (HLC1550). This application note provides a long-lifetime and cost-competitive power solution based on the TPS61094. The TPS61094 is an ultra-low Iq (60 nA) buck/boost converter device with a supercapacitor management feature. This device allows the smart meter customers to replace the HLC with a supercapacitor to reduce the cost and also control the $LiSOCl_2$ battery's discharge current to extend battery life. The TPS61094 solution can increase operation time by 20%, reduce component count by 50% and decrease the total cost.

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1 Introduction of the Smart Meter

Smart meters, including gas and water meters need to record information such as gas or water consumption and then communicate this information to a data center. Wireless communication commonly uses methods such as, NB-IoT, LoRa and ZigBee®. Take NB-IoT as an example, the typical range of input voltage of a NB-IoT module (such as the ZTE ZM8300G module) is from 3 V to 4.2 V, with a typical voltage of 3.6 V (reference 1). The current consumption is similar to Figure 1-1. The typical peak current is about 250 mA.

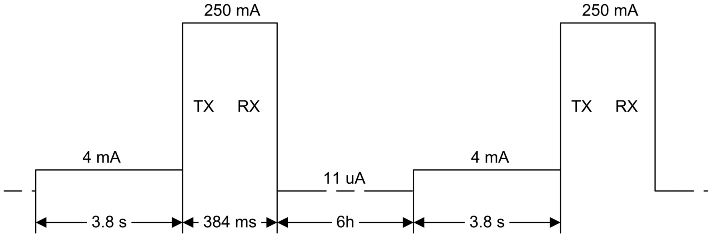

Figure 1-1. Typical Current Consumption of NB-IoT

Most smart meters are powered by $LiMnO_2$ (lithium manganese dioxide) or $LiSOCl_2$ batteries and need to support 10 years or more of operation. Because the voltage of a $LiSOCl_2$ battery (about 3.6 V) is higher than a $LiMnO_2$ battery (about 2-3 V), a $LiSOCl_2$ battery can better support a 3-V electromagnetic valve, which why it is a more popular choice for smart meter applications. The weakness of a $LiSOCl_2$ battery is that the maximum continuous current and pulse current capability is limited. Take an 8.5 Ah $LiSOCl_2$ battery (Tadiran TL-4920(ER26500)) as an example, the maximum recommended continuous current is 75 mAand the maximum 1 sec. pulse capability is 200 mA (reference 2). Because of this, it is common to parallel the hybrid layer capacitor (HLC) or the supercapacitor with the $LiSOCl_2$ battery to support the high pulse current for data transmission. Another characteristic of the $LiSOCl_2$ battery is that the battery capacity is related to the discharging current and the working temperature as shown in Figure 1-2 (reference 2). The battery capacity is about 8.5 Ah with 3-mA discharging current at 25 °C, which is shown in the ER26500 data sheet. However, the capacity drops to 2 Ah (a 76% reduction) with a 100 mA load. It is better to control the discharge current of a $LiSOCl_2$ battery to get a higher capacity and thus, increase the working lifetime (reference 3).

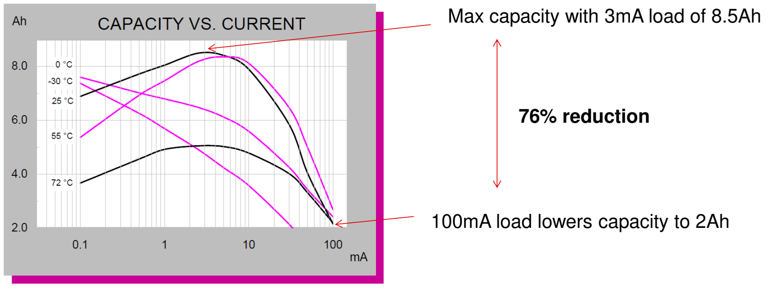

Figure 1-2. Capacity vs. Discharging Current and Temperature

2 The Traditional Power Solution of the Smart Meter

2.1 Connecting the Battery Directly

The traditional solution is the direct battery connection solution, like Figure 2-1. The communication model such as NB-IoT is connected with the $LiSOCl_2$ and HLC package directly. The voltage of the $LiSOCl_2$ and HLC package is about 3.6 V at room temperature. When the smart meter does the transmission, the HLC supports the high pulse current for the NB-IoT. During sleep mode, the $LiSOCl_2$ charges the HLC and supports the whole system consumption.

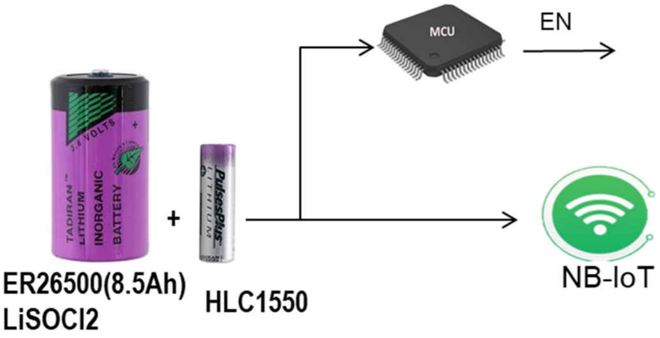

Figure 2-1. Direct Battery Connection Solution

The disadvantage of the direct battery connection solution is customers must choose HLC1550 instead of HLC1520. Because the $LiSOCl_2$ and HLC package has the poor performance at cold temperature (-25 degC or -40 degC) , like in Figure 2-2 and Figure 2-3. Figure 2-2 is the performance of ER26500 and HLC1520 at high pulse current (250 mA / 250 ms). In the waveform, the voltage of the battery package is down to 3.4 V at high pulse current. It is too little margin to power the whole system. Figure 2-3 is the performance of ER26500 and HLC1550, because HLC1550 has a bigger size and higher current capability, the voltage is down to 3.6 V, and it can support the whole system and do the transmission. But HLC1550 has bigger size and higher cost.

Another disadvantage of this solution is the discharge current of $LiSOCl_2$ is uncontrolled. In the Figure 2-2 and Figure 2-3, the discharge current of $LiSOCl_2$ is up to 15 mA and 5 mA, respectively. The $LiSOCl_2$ cannot achieve the maximum capacity, referring Figure 1-2.

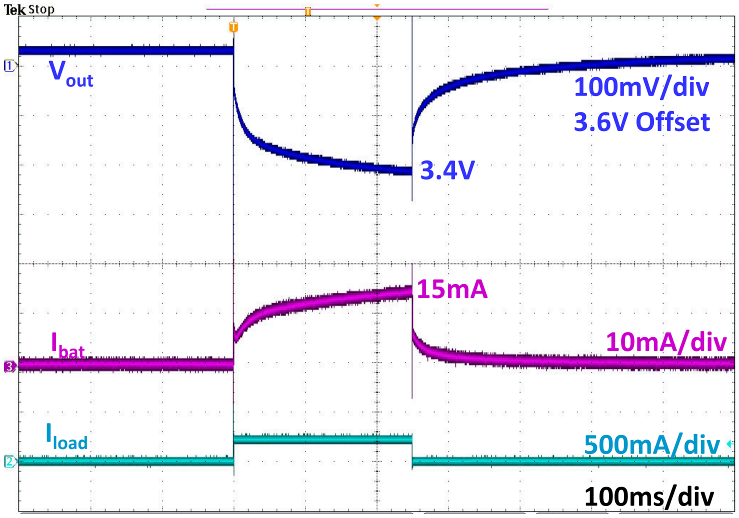

Figure 2-2. The Performance of ER26500 and HLC1520 at -25 degC

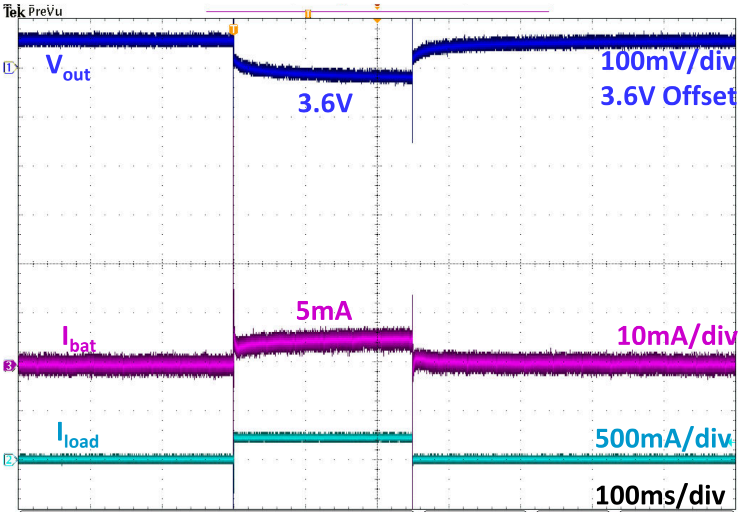

Figure 2-3. The Performance of ER26500 and HLC1550 at -25 degC

2.2 The Pure Boost TPS61094 or TPS610995 Solution

One of the cost competitive solutions is the pure boost (TPS61094 or TPS610995) solution (reference 4), similar to Figure 2-4. In this solution, customers could use HLC1520(vender: Tadiran), SPC1520(vendor: EVE) or UPC1520(vender: HCB) and they need to add a pure boost (TPS61094 or TPS610995) to regulate output voltage to about 3.6 V over the whole temperature range. This solution is not sensitive to HLC vendor and size, so the total cost is more competitive than the connecting battery directly.

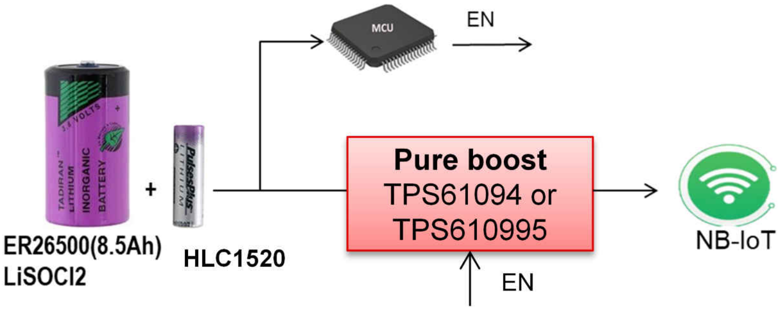

Figure 2-4. The Pure Boost TPS61094 or TPS610995 Solution

The weakness of the pure boost solution is that the discharge current of $LiSOCl_2$ battery is uncontrolled. We cannot get the maximum $LiSOCl_2$ battery capacity, and the end-off voltage of the battery package is not controllable. If the terminal voltage is too low(< 2 V), it has unrecoverable effects on the battery lifetime.

3 The TPS61094 with Supercap Solution

The TPS61094 could offer a solution exchanging the HLC to a supercap, which can reduce the total solution cost while still controlling the $LiSOCl_2$ battery discharge current to achieve the maximum capacity and working lifetime, as shown in the Figure 3-1.

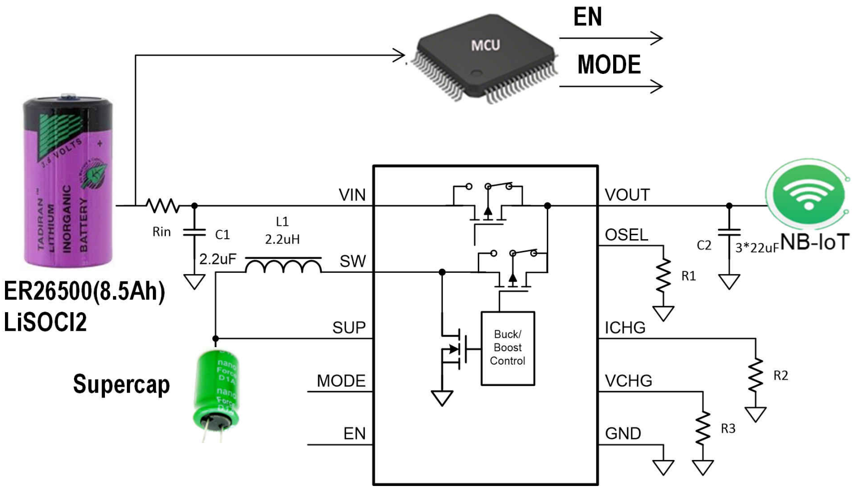

Figure 3-1. The TPS61094 with Supercap Solution

3.1 TPS61094 Description

The TPS61094 is a synchronous bi-directional buck/boost converter with a bypass switch between input and output (reference 5). When the TPS61094 works in buck mode to charge the supercap, the charging current and the charging termination voltage are programmable with two external resistors (R_3 and R_2). When the TPS61094 works in boost mode, it can boost the supercap and regulate output voltage to the programmed voltage, set by R_1.

The TPS61094 has four operation modes: the auto buck or boost mode; the force buck mode; the force bypass mode and the true shutdown mode, set by the EN and MODE pins. Customers can choose the suitable mode based on their application.

The TPS61094 has 60-nA quiescent current in buck mode or boost mode and 4-nA quiescent current in force bypass mode, which could help the system achieve long lifetime.

3.2 System Operation Description

In the TPS61094 with supercap solution, the MCU doesn't need to control the TPS61094. TPS61094 can switch between buck charging mode and boost mode automatically. It can boost the supercap to power the high pulse load at data transmission and then charge the supercap during standby mode.

By setting EN = High and MODE = High, the TPS61094 is enabled to work in the auto buck or boost mode. TI suggests to set output target voltage (setting by R_1) is 3.3 V (> 3.6 V – 150 mV), which could help TPS61094 enter the buck charging mode automatically; set charging current to 5 mA, which could help get the maximum $LiSOCl_2$ capacity, according to Figure 1-2; set charging terminal voltage to about 2 V, which could help supercap get lower leakage current and longer working life time.

TI suggests to add a series resistor (R_{in}) of about 40 Ω between $LiSOCl_2$ battery and TPS61094 VIN pin. It could help limit the $LiSOCl_2$ battery discharge current during data transmission. The $LiSOCl_2$ battery discharge current is as

$$I_{limit} = \frac{V_{LiSOCl2} - V_{OUT\_target}}{R_{in}} = \frac{3.6 - 3.3}{40} = 7.5mA \tag{1}$$

The TPS61094 operation is as shown in the Table 3-1. During stand-by operation in the smart meter, because input voltage is higher than output voltage + 100mV, the TPS61094 enters auto buck mode. The bypass MOS turns on and NB-IoT is powered by $LiSOCl_2$. TPS61094 charges the supercap until it is fully charged. When the NB-IoT does the Rx / Tx transmission, there is a high pulse current at the output of TPS61094, because $LiSOCl_2$ can't support high pulse current, the input voltage will drop. When TPS61094 detects the input voltage is lower than output voltage + 100mV, the boost mode actives automatically. So the supercap mainly supports the high load current.

Table 3-1. The Operation in TPS61094 of the Supercap Solution

System operation	Condition	TPS61094 operation
Stand-by; low-current consumption	Vin > Vout_target + 100mV	Active buck charging mode; charge supercap and keep it fully charged; Bypass MOS turns on; Vout connects with Vin; NB-IoT is powered by $LiSOCl_2$.
Doing Rx / Tx transmission	Vin >= Vout_target Vout = Vout_target	Active boost mode; at high-pulse load, supercap mainly supports the load.

4 Solution Comparison

There is a summary of these three power solutions in Table 4-1. TPS61094 could provide a cost competitive and long lifetime solution in the smart meter. This solution can help smart meter customers exchange hybrid layer capacitor (HLC) to supercap, which could have lower total solution cost.

The TPS61094 with the supercap solution can support 18.4 years and increase operation time by 20% than the pure boost solution. And because the TPS61094 shares the same inductor and input/output capacitors in the supercap charging and discharging, the TPS61094 reduces component count by 50%.

Table 4-1. The Smart Meter Power Solution Comparison

Solution	Lifetime estimation (years)	Advantage	Disadvantage
The direct battery connection solution	18.1	Simple design	Big size HLC1550 (Tadiran)
The pure boost(TPS61094 or TPS610995) solution	14.9	Smaller size HLC and no sensitivity to the vendor, like SPC1520	Cannot get the maximum $LiSOCl_2$ capacity because $LiSOCl_2$ discharge current is uncontrollable $LiSOCl_2$ discharge end-off voltage is uncontrolled; it may have unrecoverable effects on the battery lifetime
The TPS61094 with the supercap solution	18.4	Cost competitive with the supercap Control $LiSOCl_2$ discharge current and end-off voltage Automatically transition; No need for MCU control	The supercap has leakage current, need to use lower terminal voltage, like 2 V

Note:

The smart meter lifetime estimation is based on the following conditions:

- Calculation is based on Tadiran(LiSOCl2 TL-5920) and the capability de-rated according to the Figure 1-2.
- Assumption that ten months is 25 ℃ and two months' temperature is lower than 0 ℃.
- NB-IoT power consumption is about 134 mAh each year at supply voltage is 3.6 V
- LiSCL2 Battery self-discharge: 25 ℃: 1 % / year, 40 ℃: 2 % / year
- Hybrid layer capacitor self-discharge: 25 ℃: 3 μA, 40 ℃: 6 μA
- Super capacitor leakage current: for 3 F cap, working at 2.0 V can reduce the leakage current to 20 %, the leakage current: 25 ℃: 1 μA (5 μA * 20 %), 40 ℃: 2 μA
- Battery activation is about 30.4 mAh each year
- Valve power consumption is about 35.8 mAh each year
- Standby power consumption (including MCU, counting hall sensor, anti dismantling hall sensor, power supply, NB-IoT standby power consumption) is about 87.6 mAh.

5 Supercap Behavior and Design

5.1 Supercap Life Time

The supercap lifetime is related to the operating temperature and operating voltage. The classical aging model for supercapacitors is Eyring's law that estimates the aging rate, as the Equation 2. This law stipulates that a 200-mV voltage surplus increases the aging by a factor of 2 and have the same effect as a temperature increase of 10 °C. (reference 6, 7, 8)

$$t_{cal}(V;T) = t_{ref} * (2^{\frac{V_{ref}-V}{V_0}}) * (2^{\frac{T_{ref}-T}{T_0}}) \qquad (2)$$

where

t_{ref} Reference lifetime (hours)

V_{ref} Reference applied bias voltage (V)

T_{ref} Reference aging temperature (K)

The smart meter customer can lower the operation voltage according to their life time and operation temperature requirement. There is the estimation lifetime from VINA Tech 3.0V series supercap, as shown in Table 5-1

Table 5-1. VINA Tech Estimation Lifetime – 3.0 V Series

Temp Voltage (V)	25 °C Year	30 °C Year	40 °C Year	50 °C Year	60 °C Year	70 °C Year	75 °C Year	80 °C Year
2.1	180.5	127.7	63.8	31.9	16.0	8.0	5.6	4.0
2.2	127.7	90.3	45.1	22.6	11.3	5.6	4.0	2.8
2.3	90.3	63.8	31.9	16.0	8.0	4.0	2.8	2.0
2.4	63.8	45.1	22.6	11.3	5.6	2.8	2.0	1.4
2.5	45.1	31.9	16.0	8.0	4.0	2.0	1.4	1.0
2.6	31.9	22.6	11.3	5.6	2.8	1.4	1.0	0.7
2.7	22.6	16.0	8.0	4.0	2.0	1.0	0.7	0.5
2.8	16.0	11.3	5.6	2.8	1.4	0.7	0.5	0.4
2.9	11.3	8.0	4.0	2.0	1.0	0.5	0.4	0.3
3.0	8.0	5.6	2.8	1.4	0.7	0.4	0.3	0.2

Note: 30% capacitance degradation is considered as the end of life (reference 9).

5.2 Supercap Leakage Currrent

The supercap leakage current is an important part of performance in the smart meter, which is related to the operating life time. The leakage current depends on temperature, working voltage, capacitance and other parameters (similar to charge duration and short-term history) (reference 10).

For the leakage current, when the supercap working voltage decreases, the leakage current could also decrease, similar to Figure 5-1. For example, the supercap works at 1.8 V, the leakage is about 8 uA (18 % of data sheet spec) at 25 ℃.

The supercap leakage current is related to working temperature, too. The supercap leakage current at 65 ℃ is about 3~4 times as the 25 ℃, in the Figure 5-1.

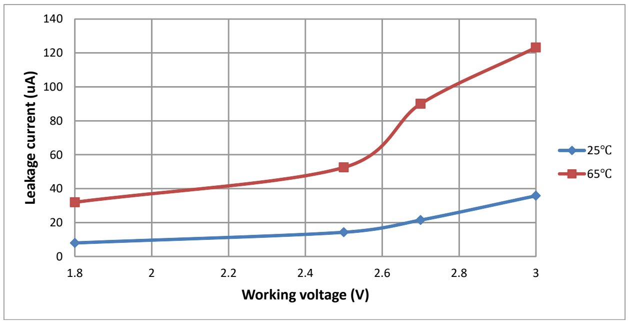

Figure 5-1. Supercap Leakage Current vs. Voltage and Temperature

Note: the test data is based on WEC3R0156QG (3 V 15F) (reference 9).

5.3 Supercap Parameter Design in TPS61094 Solution

Because the supercap lifetime and leakage current are strongly related to working voltage, TI suggests to set supercap charging terminal voltage to 2 V, which could achieve 20 years life time at 65 ℃ and the leakage current is about 18% of the datasheet spec.

The capacity of the supercap depends on Rx/Tx transmission loss. Let's take NB-IoT as the example. Assume the transmission internal is 24 h that is once data exchange every day, 3.3 V supply voltage, and a payload of 200 Bytes. The power consumption of one transmission is about 4 J. To leave 20 % margin, the target storage energy is set as 4.8 J (reference 11 and 12). The TPS61094 could support the supercap operation until supercap voltage is down to 0.7 V. So the supercap will discharge from 2 V to 0.7 V, the total discharge power is

$$P_{supercap} = \frac{1}{2} * C * (V_1^2 - V_2^2) = \frac{1}{2} * C * (2^2 - 0.7^2) = 1.755C \tag{3}$$

The supercap discharge power should be higher than the total loss of NB-IoT transmission, 4.8 J, so smart meter could choose 3 F supercap.

6 Test Report Based on TPS61094 Solution

6.1 Test Waveform

The TPS61094 with supercap solution test waveform overview is as shown in the Figure 6-1. There are three phases in this solution. Phase 1 is the NB-IoT data transmission. The load current is about 250 mA for 250 ms. The TPS61094 could regulate output voltage to 3.3 V and control the battery current within 5 mA. In the phase 2, the NB-IoT stops doing the data transmission, so TPS61094 charges the supercap in setting current about 2.5 mA. As shown in the Figure 6-1, the supercap voltage increases and triggers charging terminal voltage (2 V). The TPS61094 stops charging and this is phases 3. The whole system enters the standby mode and waits for the next NB-IoT transmission.

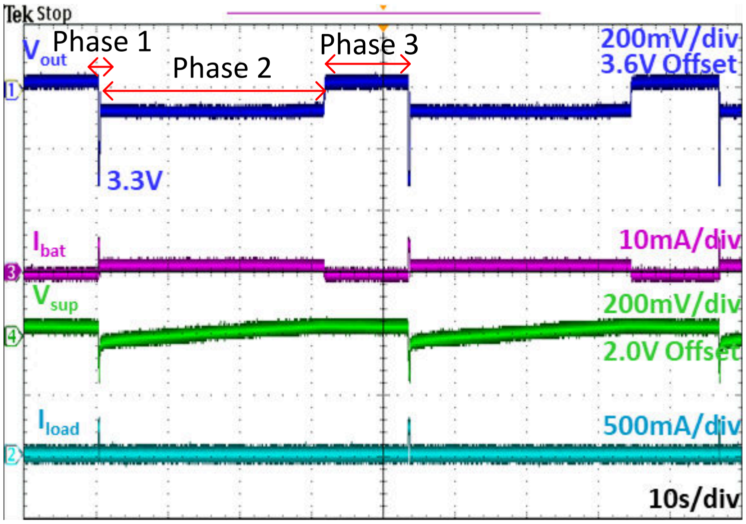

Figure 6-1. The Performance Overview of the TPS61094 with Supercap Solution

Note:

The dark blue signal (Channel 1) is TPS61094 output voltage, The purple signal(Channel 1) is LiSOCl2 battery output current, The green signal(Channel 4) is the supercap voltage, The light blue signal(Channel 2) is load current.

6.1.1 NB-IoT Data Transmission

The NB-IoT data transmission (phase 1) zoom in waveform is as shown in the Figure 6-2 and Figure 6-3. It can be seen that during high pulse current load emulating NB-IoT module, the output voltage of TPS61094 is regulated at 3.3 V to maintain normal work of system. At the same time, the output current of $LiSOCl_2$ battery is about 5 mA or 6 mA both at -25 degC and 25 degC, so that the $LiSOCl_2$ battery lifetime can be maximized referring Figure 1-2.

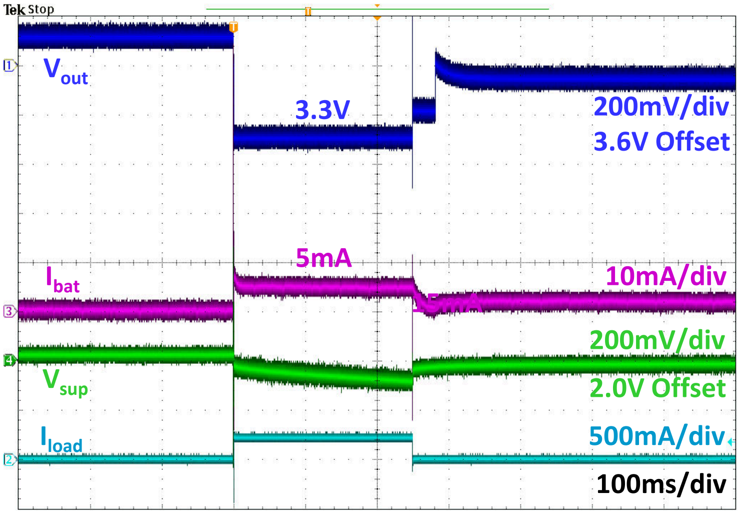

Figure 6-2. The Performance of TPS61094 with Supercap Solution at -25degC

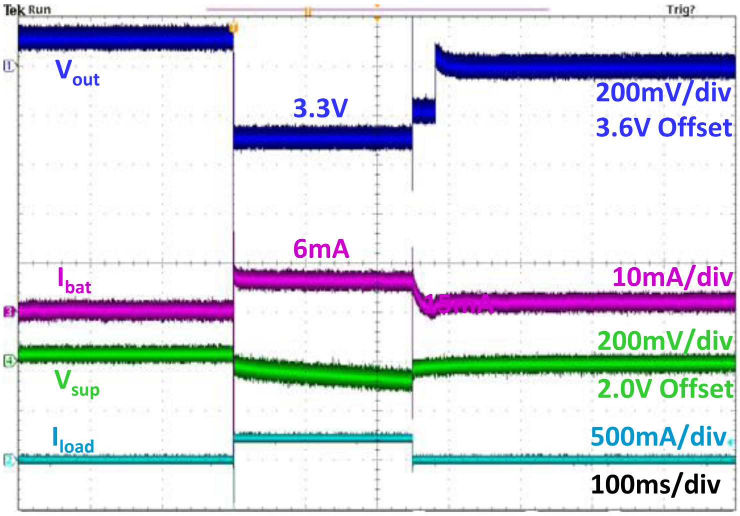

Figure 6-3. The Performance of TPS61094 with Supercap Solution at 25degC

6.1.2 Supercap Charging

Figure 6-4 shows the performance of the supercap from charging to full charge (phase 2 to phase3). During supercap charging phase, the TPS61094 can control the charging current to the set current. Because the resistor Rin(between LiSOCl2 battery and TPS61094 V_{IN} pin), there is about 55 mV voltage drop in the TPS61094 output. When the supercap voltage reaches the set terminal voltage, the TPS61094 stops charging.

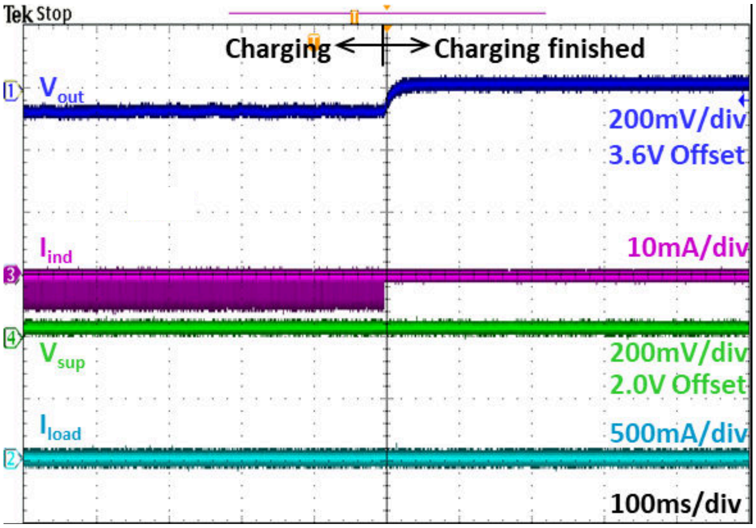

Figure 6-4. The Performance of the Supercap from Charging to Charging Finished

6.2 Efficiency

The Figure 6-5 is the 3.3-V Vout efficiency graph in boost operation. The efficiency is about 93 % at Vin=2 V Vout=3.3 V Iout=250mA.

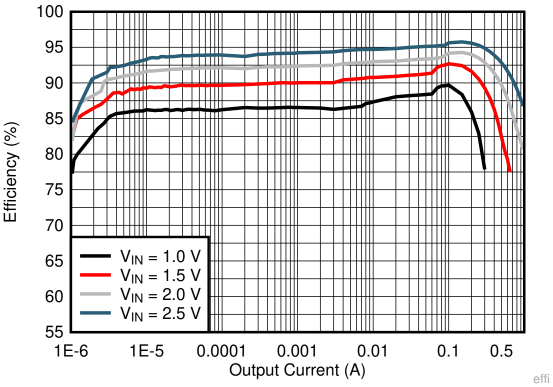

Figure 6-5. 3.3-V Vout efficiency in boost operation

The Figure 6-6 is the 3.6-V Vin efficiency graph in buck operation. The efficiency is about 88 % at Vin=3.6 V VCHG=2 V ICHG=2.5 mA.

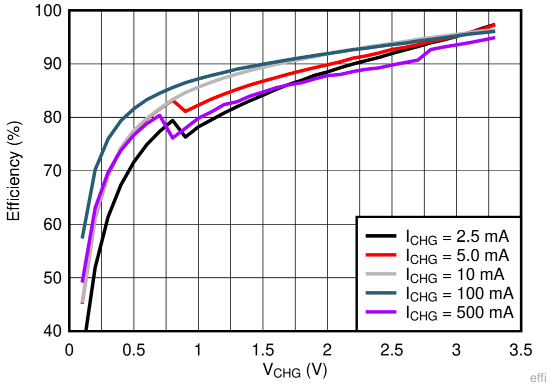

Figure 6-6. 3.6 V Input efficiency in buck operation

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8 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (March 2021) to Revision A (October 2021)	Page
Updated *The TPS61094 solution can increase operation time by 2%...* to *The TPS61094 solution can increase operation time by 20%...*	1
Updated *...decrease cost by 60%...* to *...decrease component count by 50%...*	1

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